Perceptual and Cognitive Load in Autism – An Electrophysiological and Behavioural Approach

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Thesis submitted for the degree of Doctor of Philosophy (PhD) in Psychology in May 2021

Declaration:

I, Jana Brinkert 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.

The work following work was carried out at the Centre for Autism Research and Education, University College London, under the supervision of Doctor Anna Remington, Doctor Nick Berggren and Professor Nazanin Derakhshan.

To complete the study presented in Chapter 5, a donation of 35 Muse headbands was received by the manufacturing company Interaxon Inc, which were then gifted to the participants to thank them for their participation. Interaxon Inc. was not involved in the study design or data analysis. Chapter 5 was supported by Mitacs Globalink which enabled Julie Cumin to complete an 8-week placement as part of her MSc at the Centre for Research in Autism and Education at UCL and helped in setting up the research project, participant guidelines and a pilot study for the meditation study

Abstract

Attention is a fundamentally important cognitive process and is required to efficiently navigate the world. Whilst altered attentional processes have been frequently observed in autistic people the differences seen suggest that attentional processes are different, however not necessarily deficient. In fact, aspects of superior visual perceptual ability and enhanced perceptual capacity have frequently been reported. The goal of the present thesis was to extend our knowledge of enhanced perceptual capacity under the framework of the Load Theory and to extend the findings to more active components of attention.

To address this aim, the first three empirical studies I conducted, assessed selective and executive attention in autism and in a fourth study I investigated the feasibility of a neurofeedback intervention. Specifically, in Chapter 2, I used behavioural markers of congruency effects to consider whether cognitive capacity would be increased for autistic people, analogous to the enhanced perceptual capacity previously reported. In Chapter 3, I investigated electrophysiological aspects of visual working memory capacity and filtering efficiency. The findings were further expanded upon in Chapter 4 by directly contrasting visual working memory capacity and perceptual capacity using electrophysiological markers. Finally, I sought to assess whether practical steps could be taken to address altered attention experienced by autistic adults. The feasibility of an online neurofeedback intervention was investigated to assess whether aspects of attention and mental health could be improved through the training programme (Chapter 5). The findings of the thesis were then summarised and further discussed, highlighting the contribution to the autism

attention literature and offering practical recommendations to harness attentional strengths in autism.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

APA	American Psychiatric Association
ASRS	ADHD Self-report Screener
ADHD	Attention Deficit Hyperactivity Disorder
BOLD	Blood Oxygenation Level Dependent
CDA	Contralateral Delay Activity
DASS	Depression Anxiety Stress Scale
DSM	Diagnostic Statistical Manual
EEG	Electroencephalography
ERN	Error related negativity
ERP	Event Related Potential
fMRI	Functional Magnetic Resonance Imaging
FSIQ	Full Scale IQ
IQ	Intelligence Quotient
MRI	Magnetic Resonance Imaging
N2pc	N2 posterior contralateral
NICE	National Institute of Clinical Excellence
OCA	Obsessive Compulsive Disorder
OSF	Open Science Framework
SPCN	sustained posterior contralateral
SPQ	Sensory Perception Quotient
SRS	Social Responsiveness Scale
STAI	State Trait Anxiety Inventory
WHO	World Health Organisation

Impact Statement

Attention plays a fundamental role in how we perceive and interact with the world. Attention is thought to be altered in autistic people, however, the underlying mechanism of attention is not yet known. This thesis aimed to further develop our knowledge of attention in autistic people using both behavioural and electrophysiological markers of attention. Understanding the underlying mechanism of attention can help to make practical adjustments to improve the ability to focus in autism. In turn, this might improve education, employment and therapeutic outcomes. As such, the practical application of improving attention was assessed via an online meditation intervention study.

The work presented in my PhD thesis was disseminated through talks and symposia at UCL and internally in the research centre. All four experimental chapters will be submitted to publications in autism related journals. Some of the work presented in this thesis has been presented at international and national conferences at the British Psychological Society Cognitive Section and the International Society for Autism Research.

To engage with the wider community I organised and conducted several public engagement workshops to showcase our research and help people understand the contextual neuroscience and the electrical activation in the brain, using the real-time neurofeedback headsets (also used in chapter 5). The workshops were held as part of: the UCL “Bloomsbury festival”, “It is all academic” and an event for prospective students in the UCL Institute of Education.

All outcomes of the work presented in this thesis have been, or will be, summarised in easy-to-follow summaries to disseminate the findings amongst the participants, to allow them to find out what the results of the study they have contributed to are, and to show our appreciation for their commitment to the development of understanding and knowledge.

Acknowledgements

I would like to thank my wonderful PhD supervisor Anna Remington. You always go the extra mile, from the first day when you accepted me as an additional Master student in excess of your supervision allocation and provided me 100% support since. You are the most encouraging and supportive supervisor anyone could wish for and have had a remarkable impact on me and my academic development. I am excited for our next research project to come. Thank you for everything!

I am also deeply indebted to Nick Berggren you stepped in as a supervisor when Anna went on maternity leave. You taught me so much about EEG analysis, programming and so much more. Thank you for your wonderful guidance throughout, I could not have done it without you!

Also, my special thanks goes to Naz Derakshan you motivated me when I needed it and adopted me to be part of your lovely lab group. Thank you to Jess and Trish who through their friendship provided invaluable support throughout my PhD journey.

A special thanks also goes to my all my brilliant CRAE colleagues (former and current) an especially to Laura for her constant encouragement and kind words, Pravina, Anne, Mel B and Julie. My amazing PhD office mates Kana, Ellie, Mel, Maria and Lorcan and my departmental PhD buddies Orianna, Dora, Myrto and Vassilis for constant support, distractions, lunches in the park, farmers market trips and so much more. I’ve learned so much from each of you and I wouldn’t be the same person without having worked with you all. The pandemic has certainly not made the last year of thesis writing easy but I am extremely grateful for my friends cheering me on from afar, a very special thank you Orli, Eli, Laura, Sarah, Dominique and Max.

I’d like to take the opportunity to thank all the participants who dedicated their time and energy and sat through 3.5 hour session with me in the EEG room or participated in the online studies and gave me feedback on various versions of pilot trials – this work would not have been possible without their commitment.

A special thanks also goes to Tim, Marion, Anthony and my “Kingsbury family” for your support, kind words and flower and food deliveries (especially the constant supply of strawberry laces got me through this thesis!). My family, Mama, Papa, Nora and Stephan, I will be eternally grateful for your love and encouragement.

Finally, the biggest thanks goes to Patrick, who persuaded me to study a year abroad which turned into 7 years in the British higher education system. You are my rock and there are no words to express how grateful I am for all your encouragement, support and love.

This thesis is dedicated to my late aunt Paula who is an enduring source of inspiration and strength.

Chapter 1
General Introduction

At any given time, we are exposed to an enormous amount of information. Attentional processes are required to focus on what is relevant and be able to achieve goal directed behaviour. This thesis will focus on attentional mechanisms, and whether theses attentional processes are altered in autistic people. More specifically, in this thesis I will explore perceptual and cognitive attentional processes in the autism literature using electrophysiological and behavioural paradigms. In addition, I examine the feasibility of a neurofeedback guided training study and assess whether the intervention supports improved attention and mental health. In the present chapter, I will provide an introduction to autism, discuss the main cognitive theories of autism, describe core attentional features of attention, and review the existing literature on these core attentional mechanism in autism. Subsequently, I will outline the rationale for the studies discussed in this thesis.

Background of Autism

The History of Autism

Historical texts in the 1700s point towards descriptions of what could be described as autistic behaviour (for reviews see Evans, 2013; Wolff, 2004). However, the term *autism* was not used until 1911, when Eugen Bleuler, a Swiss Psychiatrist, published his work on schizophrenic thought and termed autism as social withdrawal (Bleuler, 1911).

Later in the 1940s, Leo Kanner an American psychiatrist, published his case report on autism. He systematically detailed the case reports of 11 autistic children, their behaviours and mannerisms (eight boys and 3 girls, aged between 2-11 years; Kanner, 1943). He found that the children preferred “aloneness” and were drawn to objects rather than people. Observations also included the children’s need for sameness and obsessive repetitive behaviours and rigid communication. Kanner also speculated that parents showed a lack of warmth and defined autism as a rare infantile condition (Kanner, 1943). His work was rooted in psychoanalysis and he believed that parental coldness was connected to autism. This inspired theories in the 60s such as the *refrigerator mother* theory (Bettelheim, 1967). Although the work was quickly discredited, it was harmful for a lot of mothers and their autistic children and became a widespread myth (for a review see Douglas, 2014).

Post Second World War, the first epidemiological studies emerged that are thought to have paved the way for the autism research of today (Evans, 2013). Lotter (1966) developed 24 behavioural categories to assess children aged between 8 -10 years of age in the British county of Middlesex. A total of 35 children were categorised as “autistic” making it a rare diagnosis with an estimated prevalence of 4.5 in 10000 children at the time.

Only a few months after Kanner’s first publication, the Austrian paediatrician Hans Asperger published his work “die ,,Autistischen Psychopathen" im Kindesalter” which translates into “the “autistic psychopaths” in childhood” that had remarkable similarities with Kanner’s work (Asperger, 1944). Based in Vienna, Asperger published his observations as part of his post-doctoral work in German and it therefore remained largely unknown in English speaking countries until circa 1981 when Lorna Wing popularised “Asperger’s syndrome” (Wing, 1981) and Uta Frith later translated Asperger’s work into English (Uta Frith, 1991). The work included the observation of four autistic boys who displayed social deficits but no intellectual impairments. Later, after the translations of Asperger’s work, the eponym “Asperger” was used as a category to describe social deficits without co-occurring language impairments and intellectual impairments (Wing, 1981).

More recent investigations placed the observations published by Asperger in their historical context, finding that Asperger was affiliated with organisations that had links with the Nazi party, shared nationalist ideologies and showed anti-Semitic behaviours. His name was associated with the medical files of children that had intellectual impairments and were subjected to the Nazi’s child “euthanasia” programme (e.g. see Czech, 2018 for a review).

When the American Psychiatric Association (APA, 1952, 1968) released the first and second edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-I, 1952 and DSM-II 1968) autism was classed as a subcategory of schizophrenia. The DSM-III saw autism as a separate category and was formally called *infantile autism* with an onset of 30 months (APA, 1980). The epidemiological study carried out by Wing and Gould followed by their paper in which they proposed *triads* of symptoms that were classified into social interaction, communication and language deficits and imagination and rigid thinking (Wing & Gould, 1979). These triads influenced the revised version of the third edition (DSM-IIIR) which was characterised as a *triad of impairment* (APA, 1987). The DSM-IV retained the triads of impairment categories (APA, 2000b). In both versions the diagnosis was called *Autistic Disorder* and also reflected the recognition of autism as a pervasive disorder that not only applies to infants. The DSM-IV had additional separate diagnoses for the categories Pervasive Developmental Disorder, Not Otherwise Specified, Asperger’s Disorder (or Asperger Syndrome), Rett’s Disorder (or Rett Syndrome) and Childhood Disintegrative Disorder.

Current Diagnostic Categories

In what is now more than a century of autism research, the diagnostic categories have changed significantly. There are currently two diagnostic manuals that are widely available; the most recent fifth edition of the DSM-5 was published in 2013 and led to some significant changes (APA, 2013b) and the International Statistical Classification of Diseases and Related Health Problems (ICD) of the World Health Organisation (WHO, 2016) offers an alternative diagnostic manual. The present version (10th edition, ICD-10) outlines differences in the diagnostic categories, including three subtypes of autism; childhood autism, Asperger syndrome and pervasive developmental disorder. The eleventh edition was released in May 2019 and will come into effect from 1st January 2022. The ICD-11 overlaps largely with the DSM-5 diagnostic criteria, although it allows for separate assessment on whether the autism diagnosis co-occurs with or without intellectual disabilities (for more details on co-occurring conditions see section on co-occurring conditions below).

To get a better understanding of autism, I will explore the diagnostic criteria of the DSM-5 in more detail. With the introduction of the DSM-5, the subcategories of autism as defined by the DSM-IV including autistic disorder, Asperger's disorder, or pervasive developmental disorder were replaced by a single category called "Autism Spectrum Disorder" (henceforth "autism") in the DSM-5. The diagnostic criteria include deficits in social communication and interaction (social domain) as well as restricted and repetitive behaviours and interests and sensory processing (non-social domain). The first domain describes social and emotional reciprocity, which for instance describes issues with conversational "back and forth". Secondly, non-verbal communication such as maintaining eye contact or the use of gestures and facial expressions may be atypical. This could mean that the distance to the conversing partner is too close or too distant. The third category includes issues in maintaining and understanding relationships and adjusting to social contexts. For a diagnosis of autism on the social domain all subcategories must be met. In the non-social domain two of the four following categories have to be met; 1) stereotyped and repetitive motor movements during speech or when using objects, 2) insistence on sameness of routines, 3) restricted interests, 4) hyper- and hypo-reactivity to sensory information. These categories are typically heterogeneous and rigid and may vary in their frequency and intensity and can make it difficult for an autistic person to engage socially or in and educational or professional environment (for a recent review see Berry et al., 2018). For a person who receives an autism diagnosis, these behaviours could manifest in wide ranging types of behaviours or rituals, for instance that could result in lining up objects (e.g. groceries or toys) accurately or repetition of sounds or previous words in a conversation i.e. echolalia. The autistic person[1] might also show a need for taking the same route to work or school each day or insisting on eating the same food. Anecdotally when these routines and transitions are not met this causes extreme distress for the autistic person. Autistic people may also show an intense interest or unusual captivation and intensity for certain objects (e.g. toys) or show obsessive interest, for instance in historical events or film sequences (e.g. knowing all details about James Bond films). Sensory reactivity has been added to DSM-5 as a new diagnostic criterion. All sensory domains can be affected by it which could for instance mean a stronger aversion and sensitivity to smells or a reduced sensitivity to temperatures. Not all sensory experiences must be negative. Whilst autistic people sometimes report enjoyment of sensory experiences, sensory reactivity can also lead to adverse experiences such as overloads and melt downs (Robertson, 2012).

In addition, the DSM maintains that during the autism assessment autism is classed as a neurodevelopmental condition that typically manifests during childhood (American Psychiatric Association, 2013). It has to be noted that the symptoms might only emerge when social demands are high and those symptoms may also be masked or camouflaged by learned strategies later (Hull et al., 2017; Lai et al., 2017; Livingston & Happé, 2017). According to the

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[1] Identity first language (e.g. “autistic person”) is favoured over person first language (e.g. “person with autism”) by a majority of autistic people (Kenny et al., 2016) and will therefore be used throughout the thesis.

DSM-5 the symptoms have a significant impact on employment and social life. Furthermore, the DSM-5 suggests that during the autism assessment, further co-occurring mental health, genetic and neurodevelopmental conditions should be assessed. Likewise, a diagnosis of co-occurring intellectual disabilities is possible, should a global intellectual disabilities or a developmental delay not provide a more suitable diagnosis. Diagnostic pathways, prevalence rates, co-occurring conditions and the aetiology of autism will be further discussed in the next section.

Diagnostic Pathway in the UK and Prevalence Rates.

In the UK, for those under 19 years of age an autism diagnosis is based on both the DSM-5 and ICD-10. A local multi-disciplinary team is in charge of the diagnostic process (National Institute for Health and Care Excellence, [NICE] 2017). The team usually consists of a paediatrician or adolescent psychiatrist, a speech and language therapist and a clinical and/ or educational psychologist. Whilst the symptoms are typically noticed during childhood when there are developmental differences between autistic and non-autistic children, adults in the UK are also increasingly being referred for an autism diagnosis (Happé et al., 2016). The diagnostic process is similar for adults. In an initial meeting takes place to identify challenges and whether the core challenges are met for an autism diagnosis (NICE, 2016). After the initial brief assessment, a more complex assessment is conducted using some of the assessment tools listed below. Recent studies suggest that adults seeking a diagnosis have frequently experienced a lack of available assessments and lack of tailored post diagnostic support for adults (Crane et al., 2018). Similarly dissatisfaction was also noted by parents whose children underwent an autism diagnosis in the UK (Crane et al., 2016). Concerns were frequently raised about long waiting times, information provided at the time of the diagnosis, the stress associated with the diagnosis and post diagnostic support.

As it transpired from the diagnostic categories as well as the challenges in classifying autism diagnostic categories, the symptoms are highly heterogeneous in the clinical presentation and the severity and manifestation of the social and non-social symptoms (Jeste & Geschwind, 2014; Masi et al., 2017). As there are no reliable biological markers available, the diagnostic assessment largely relies on structured behavioural observations and behavioural checklists and self-report assessments to test whether the symptoms are present in line with the diagnostic criteria.

Tools that are used to assess an autism diagnosis encompass the Autism Diagnostic Observation Schedule (ADOS-2, Lord et al., 2012), the Autism Diagnostic Interview revised (Lord et al., 1994), the Adult Asperger Assessment (Baron-Cohen et al., 2005), Asperger syndrome and high-functioning) diagnostic interview (Gillberg et al., 2001). In addition self-report (or caregiver or teacher reports depending on age and abilities) measures such as the Social Responsiveness Scale version 2 (SRS-2, (Constantino & Gruber, 2012) and Autism Quotient (Baron-Cohen et al., 2001) help to identify and quantify autism and are often used as a complementary measure to observational and interview assessments, or as a screening tool (NICE, 2016).

Whilst early epidemiological studies suggested that autism is a rare disorder (Lotter, 1966), the current estimates of the Centre for Disease Control in the US suggest that one in 59 (1.69%) of the population under 21 is autistic (Baio et al., 2018). The incidence rates are continuously updated and thought to have increased over the past decades in the United States (Maenner et al., 2020) and indeed, a recent consensus study utilizing school records in the UK shows similar increases in prevalence rates (McConkey, 2020). The rise in the prevalence rate is likely to be reflected by the broadening of the diagnostic categories for autism (Hayes et al., 2018), improved assessments for intellectual and cognitive abilities (Hallahan et al., 2020)and opening up the diagnosis in adulthood (Happé et al., 2016) and the increasing awareness and education around autism (Elsabbagh et al., 2012). However, there is a lot of disparity between reported prevalence rates. The higher prevalence rates are typically based on data originating in Western, developed countries (Elsabbagh et al., 2012). In addition, low-income countries present lower estimates. This likely reflects poorer education and healthcare in those countries, and suggests that many autistic people in those countries go undiagnosed and without the required support.

There is also a notable gender difference in autism diagnoses, the male-female ratio is around 4:1 reported (Fombonne, 2009). However, Loomes et al. (2017) conducted a meta-analysis with 54 studies and suggested that when the studies were of higher methodological quality (i.e. reduced risk of bias), the ratio of diagnosis was closer to three men to every woman. In addition, autistic females are more often missed during the diagnostic procedures (e.g. Duvekot et al., 2017), this might be related to increased levels of diagnostic tools being developed and validated with a male autism sample (Kirkovski et al., 2013) but also due to a different presentation of a female autism phenotype and higher levels of camouflaging (i.e. compensating and masking symptoms, Hull et al., 2020)

Co-occurring conditions

Whilst increased prevalence of co-occurring conditions for autistic people were long speculated (e.g. Gillberg et al., 2001), only the introduction of the DSM-5 allowed additional diagnosis of co-occurring psychiatric and medical conditions (APA, 2013b). The following subsections review co-occurring intellectual impairments as well as common psychiatric and medication conditions in autism.

Intellectual Impairments

As touched upon in the diagnostic assessment of autism, the variability of intellectual abilities is high within the autistic sample. Intelligence is typically tested using standardised Intelligence tests using the intelligence quotient (IQ), where an IQ below 70 is defined as an intellectual impairment. It is estimated that out of those who meet an autism diagnosis up to 33-55% are considered to meet the diagnostic criteria for intellectual impairments with an IQ below 70 (Baird et al., 2006; Charman et al., 2011; Maenner et al., 2020). Given the large proportion of people who have a co-occurring intellectual impairment, it is even more concerning that those with intellectual disabilities have been largely overlooked in research. For instance, a Web of Science search with the key words “autis” and “intellectual impairment” or “low functioning” between 1900 and 2021 yielded 1128 results out of which most studies are genetic studies and only 202 results fell under the category of psychological and developmental research (with a slight increase over the past few years. Nonetheless, not much is currently known about autistic people with co-occurring intellectual impairments.

Autistic people with intellectual disabilities also often display language and memory impairments (Boucher et al., 2008). Fombonne and colleagues (2020) conducted an epistemological study in which they investigated co-occurring conditions of autistic children in a US sample who were placed under legal guardianship (this does not directly mean that this due to an intellectual disability but can also be related to additional needs). In this sample, care giver and legal guardianship reports revealed that 9.2% were non-verbal and 22.9% minimally verbal. In the sample 15.5 % had also been diagnosed with a seizure disorder. Participants also had problems with sleep (39.4%) and eating problems (29.4%). Overall there is an increase in psychiatric disorders in those autistic participants with intellectual impairments compared to those without (Fombonne et al., 2020), however a recent study suggests that this is not the case for depressive symptoms in a sample of middle aged and older autistic participants (Bishop-Fitzpatrick & Rubenstein, 2019). Apart from prevalence rates, not much is known about the cognitive profile of autistic people with intellectual impairments. One study suggests that autistic people with a lower IQ are more likely to show adaptive function issues compared to those with high level of IQ (Bölte & Poustka, 2002). The lack of studies involving participants raises question as to whether the cognitive profile of autism is yet understood. Methodological challenges and often reported reduced speech and language abilities make cognitive testing challenging (Goldsmith & Skirton, 2015). More implicit measures such as using eye gaze and anticipatory looking tasks may help to better understand the cognitive profile of autistic people (Gaigg, Krug, et al., 2020).

Mental Health Conditions and ADHD

The likelihood for a co-occurring mental health condition in autism is increased compared to the general population, for instance Lever and Geurts (2016) reported that 79% of autistic adults have one or more co-occurring mental health conditions during their lives. Overall, anxiety disorders are high in autistic people, with estimates at around 23- 34% (Hofvander et al., 2009; Joshi et al., 2013; Lai et al., 2019; Lever & Geurts, 2016). More specifically, Hofvander et al. (2009) reported that 15% had a generalised anxiety disorder, 13% social anxiety and 6% panic disorders. The life-time prevalence for anxiety disorders is thought to be between 42- 53.6 % (Hollocks et al., 2019; Lever & Geurts, 2016). In comparison, in the general population the life time prevalence of suffering from anxiety disorders is estimated at 33.7 % (Bandelow & Michaelis, 2015).

Similarly, the lifetime prevalence for receiving a diagnosis of depression is 4 times higher for autistic people compared to non-autistic people and is approximately 8% in autistic children and adolescents (Hudson et al., 2019) and ranged between 39% to 53.6% in autistic adults (Hollocks et al., 2019; Hudson et al., 2019; Lever & Geurts, 2016). Overall, the prevalence rates for an additional mental health condition ranges between 40.7-53% in epidemiologist samples of autistic adults (Hofvander et al., 2009; Joshi et al., 2013; Lever & Geurts, 2016) however a more recent meta-analysis including 83 studies suggests that the rates are lower at around 14 % (Lai et al., 2019). The differences in the samples might be explained by factors such as age, as rates for depressive disorders are thought to increase with age (Lai et al., 2019; Pezzimenti et al., 2019). In addition, heterogeneity in prevalence rates are thought to be related to differences in sampling and methodological approaches across studies. For instance Hudson and colleagues (2019) conducted a meta-analysis summarising 66 studies and found that rates for depression were increased when assessed through interviews rather than self-report rates. In line with this finding, Crane et al. (2019) found that the experiences of autistic people differ and they struggle to understand and evaluate their own mental health and stigma and difficulties experienced when trying to access services make it extremely difficult for autistic people to seek help.

Whilst the implications of depressions can have an extremely debilitating impact on day to day life, research suggests that the presence of co-occurring mental health challenges is associated with poorer life quality and life outcomes (Joshi et al., 2013). Suicide rates are higher in autism as well as suicidal thoughts as well as self-harm (Cassidy et al., 2020).

Other commonly assessed mental health disorders include: obsessive–compulsive disorder (OCD) 10%, schizophrenia spectrum disorders 5%, and bipolar disorders 5% (Lai et al., 2019). An additional diagnosis of Attention Deficit Hyperactivity Disorder (ADHD) was also high between 30-39 % (Joshi et al., 2013; Lai et al., 2019; Lever & Geurts, 2016).

Medical Conditions

Croen et al. (2015) found that in a sample based on Northern California reported that compared to the general population autistic people are at higher risk of immune conditions, gastrointestinal and sleep disorders, seizure, obesity, dyslipidemia (a condition with an increased amount of fat and cholesterol in blood), which ultimately raises the risk for hypertension, and diabetes (Tyler et al., 2011). In addition, prevalence rates for seizure disorder in autistic adult samples were between 11.9% and 22.2 % compared to non-autistic adults (Croen et al., 2015; Kohane et al., 2012; Tyler et al., 2011). Epilepsy is thought to vary depending on language ability and cognitive function and the prevalence rate of epilepsy is increased in autistic females (Bolton et al., 2011). Autistic people also have an increased prevalence for sleep/wake disturbances 13% (Lai et al., 2019).

Although the genetic cause for autism is currently not known, an estimated 10% of autistic children have a chromosomal disorder, which helps to identify genetic communalities of autism. For instance, genetic disorders include Rett’s syndrome, an x -chromosome linked neurodevelopmental disorder that predominantly occurs in females is linked to the MECP2 gene (Richards et al., 2015). The prevalence of autism is around 61% in females with Rett’s syndrome (Richards et al., 2015). Fragile X is caused by a mutation of the X chromosome and FMR1 gene and a recent study indicated that 60.7% of children with Fragile X met the diagnostic criteria for autism (Roberts et al., 2020). The chromosomal disorder is also associated with intellectual disabilities as well as mutations of the X-chromosome and FMR1 gene (Roberts et al., 2020). Likewise, prevalence rates for autism in other conditions are high, including Cohen’s syndrome (54%) tuberous sclerosis and Angleman’s syndrome (both 36%; Richards et al., 2015). Prader Willi syndrome is a genetic disorder that is linked to a lack of the paternal imprinted gene in 15q11-13 (Milner et al., 2005). Autism symptomatology is at around 12.5% in children with Prader Willi Syndrome those (Veltman et al., 2005). Studying genetic conditions can therefore help to identify markers that are underlying autism, the common biology and aetiology of autism will be further discussed in the next section.

Known Biology and Aetiology of Autism

A large body of research has been invested to understand the causes of autism (Lord et al., 2020). In this section a brief overview will be given on genetic and environmental factors that are related to autism, more details about the neurobiology and environmental factors of autism can be found in more extensive reviews (Modabbernia et al., 2017; Parellada et al., 2014). As previously highlighted certain variants have been associated with autism including chromosomal disorders. Likewise, twin studies and genetic variability testing in large cohorts have been used to identify genome associations with autism and specific symptoms and core features of autism (Gaugler et al., 2014). These studies indicate heritability rates that range from moderate (Hallmayer, 2011) to strong (Lichtenstein et al., 2010). In addition, family occurrence rates of autism are around 10% (Constantino et al., 2010). Over 100 genes have been associated with autism (Satterstrom et al., 2020). Genetic variants linked to protein functions at synaptic mechanisms such as SHANK3 have been identified (Durand et al., 2007; for a review of other genes and gene products that are associated with autism see Parellada et al., 2014). Proteins involved in the gamma-aminobutyric acid (GABA)ergic and glutamatergic receptors have been associated with an atypical imbalance of excitatory and inhibitory systems in autism (Masuda et al., 2019). This cortical excitatory and inhibitory imbalance is also thought to be directly related to sensory processing, inhibition on cognitive tasks (Høyland et al., 2017; Robertson & Baron-Cohen, 2017).

To help further identify molecular processes involved in the genetic architecture in autism, post mortem studies can be used to identify cellular differences in autistic compared to non-autistic people (e.g. Schwede et al., 2018). For instance, studies suggest that the GABA receptor density is reduced in autism, in line with genetic studies on GABAergic receptors (Lozano-Soldevilla et al., 2014). In addition, other studies have shown that mitochondrial expressions are downregulated in autism (Schwede et al., 2018). However, the gene and environment interaction still remains largely unknown and is mostly studied in isolation (Lord et al., 2020).

Much less is known about the environmental factors that might add to the aetiology of autism. Modabbernia et al. (2017) synthesised 80 studies in a meta-analysis and found that birth complications (including a reduced blood and oxygen supply at birth and birth trauma) were strongly associated with autism. Factors such as maternal health at birth have a weaker association with autism. Importantly, vaccination, maternal smoking and assisted reproductive technology are unrelated to autism prevalence (Modabbernia et al., 2017).

Neurological Correlates of Autism

Whilst the aetiology of autism is largely unknown, over the past few decades a large body of research was invested in researching neural correlates of autism. In this section, I will explore the candidate neurological underpinnings that are frequently highlighted in the autism literature. I will also discuss key neuroanatomical and functional evidence that has been investigated in the autism literature, lastly, I will highlight some ethical considerations around identifying biomarkers in autism.

During Magnetic Resonance Imaging (MRI) scans, a magnetic field is created using radiofrequency, differences in tissues and chemical nature can be visualised, it is therefore a powerful technique enabling understanding of structural and anatomical differences in the brain (for a review see Berger, 2002). Using MRI, Hazlett et al. (2017) conducted a longitudinal study with infants who have higher familial prevalence rates (e.g. a sibling with an autism diagnosis) and infants without familial risk. They found that within the first year of life an increased brain volume overgrowth is associated with a later autism diagnosis at 2 years. In addition, the cerebellar and pre-frontal cortex has found to be enlarged and has matured differently in autistic compared to non-autistic children. This is thought to be related to increased myelin in the neuroglia as well as decreased synaptic pruning and inflammatory responses in early development in autism.

In addition to circuit differences in early years, structural differences have been uncovered that are related to the neurocognitive behavioural differences as outlined in the diagnostic categories above. Amaral et al. (2008) reviewed anatomical differences of neural networks in relation to the pathology of autism. The anatomical differences include: fronto temporal and parietal regions (including orbito- and inferiorfrontal cortex, posterior parietal cortex), limbic structures, basal ganglia and anterior cingulate and dorsolateral prefrontal cortex as well as differences in the cerebellum. Whilst the anatomical differences highlight differences in the network structure, these differences are not unique to autism; additionally causality of the differences in brain anatomy and behaviour cannot be assumed (for a review see Ecker, 2017). For instance, differences found in the cortical orbito and inferior circuit have also been reported in OCD (Pauls et al., 2014).

Building on structural investigations, methods such as functional magnetic resonance imaging (fMRI) helped to study functional differences associated with autism. With increased neural activation, the oxygen and the blood flow in the brain changes. fMRI utilises these changes in oxygenated blood levels in the brain as an indirect measure of brain activation

(Glover, 2011). As fMRI is blood oxygenation level dependent (BOLD) and as the blood changes are slow (compared to neurochemical changes) the temporal resolution of the technique is limited, however the spatial resolution is high and offers insights into functional differences in the brain. Using fMRI, studies have investigated differences in communication and language abilities and in particular differences in increased activation of the inferior frontal gyrus and temporal gyrus as well as reduced activation in the temporal gyrus, but also point to differences in emotion and face processing as well as attention and sensory sensitives (for a review see Herringshaw et al., 2016). A comprehensive review paper by Philip and colleagues (2012) summarised 90 fMRI studies published between 1984 and 2009 on functional domains of language, visual processing, executive function and aspects of social cognition. The heterogeneity of tasks included in the review have however made direct comparisons within and across the domains challenging. Regions that indicate significant differences are related to decreased activation in prefrontal and subcortical brain regions in executive function tasks. In addition, the superior temporal gyri were modulated in autism with indications of increased activation during social tasks but a decreased activation in auditory and language tasks. The study also revealed that there are controversies around whether there is over- or under connectivity in autism across cortical areas when the brain is at rest. Indeed, the mixed findings of the under- and over connectivity across studies have until today remained a question and are possibly related to the age, matching and heterogeneity of symptoms across autism (for a review see Hull et al., 2017).

More recently, resting state fMRI evidence from large scale data using the Autism Brain Imaging Date Exchange (ABIDE; Di Martino et al., 2014) has been used to identify structural and connectivity differences of autistic and non-autistic adults. Using large databases enables us to understand the heterogeneity in autism. In large shared datasets of fMRI recordings from autistic people, recent studies have suggested that there were specific differences observed across three networks; default mode network, parieto insular and language networks (de Lacy et al., 2017). In particular, a recent study tested biomarkers such as decreased connectivity across the temporo parietal junction (involved in social cognition) and the insular and inferior partial cortex (cognitive control and attention, this will be will be further discussed in the section on attention in the section part of this thesis, Abraham et al., 2017). This was 67% effective in discriminating autistic and non-autistic participants (Abraham et al., 2017). There is however a large heterogeneity of activation across the dataset, based on age, handedness, sex and methodological differences used across the studies as well as heterogeneity within autistic participants (Geschwind & Levitt, 2007), making it difficult to identify reliable differences in autism.

Electroencephalography (EEG) is a non-invasive technique to detect changes of neural activity in the cerebral cortex. To achieve this, electrodes are placed on the scalp to pick up electrical activation in the brain. Electrical activation can be detected when postsynaptic potentials of clusters of neurons firing at once. Over the past century, EEG has been extensively used to identify sensory, cognitive or motor responses, due to the high temporal resolution of the method. In particular, evoked related potentials (ERPs) where the activation is time locked at certain events that are presented on the screen, is a powerful technique to assess activation and test whether there are differences between groups of people. ERP techniques will be used in this thesis (Chapter 3 and 4) to investigate cognitive and attentional processes and the details will be outlined later in this chapter. However, in the following section I will highlight two ERPs that have been consistently suggested to be modulated in autism.

One such marker is the N170 a negative ERP component that peaks after 170ms when viewing faces (a more negative amplitude and shorter latencies for faces as opposed to non-faces e.g. objects) has been proposed as a potential biomarker related to social communication deficits in autism (McPartland, 2016). A recent meta-analysis that compiled 23 EEG studies suggests that the increased latencies were found in the N170 component in autism

(Kang et al., 2018). There were however no differences in the amplitude of the N170, however a moderator analysis revealed that in the adult sample and those with higher cognitive abilities the N170 amplitude was decreased. The authors suggest that there might be compensatory mechanisms involved in autism when processing faces. There are however several limitations such as heterogeneity within the studies where electrode selection and analysis of the EEG data especially greatly varies.

Another paradigm used standard sound and infrequent, deviating sounds to understand the processing of novel stimuli (referred to as oddball task). The infrequent sound elicits a more negative activation 100-250ms post stimulus onset (mismatch negativity, MNN) across the frontal and midline electrodes. The difference wave observable between standard and the deviant sounds are where autistic people show a reduced amplitude and latencies (Näätänen et al., 2007). Two recent meta-analyses summarised studies that used auditory oddball tasks and one found that autistic participants have a reduced MMN amplitude and latency (Chen et al., 2020) whereas the other meta-analysis found that the amplitude and latencies were decreased but the difference was not significant (Schwartz et al., 2018). However, age seems to be moderating the effects where the reduced amplitude difference is highest in children and adolescents (Chen et al., 2020). There are however methodical challenges and small sample sizes across the EEG studies (Schwartz et al., 2018). Nonetheless, using ERP markers can help to identify underlying cognitive and attentional differences in autistic compared to non-autistic people (this will be further discussed in the attention section of this chapter).

One of the reasons why there has been a wealth of research dedicated to findings differences at a structural, anatomical, and functional level is to detect biomarkers that are related to autism. To date, however, there remain no reliable biomarkers that could effectively identify autism. One of the reasons why there are currently no clear biomarkers that can predict the onset or development of autism, might be partly related to the heterogeneity of the condition. Importantly though, there are ethical considerations that should be discussed when considering the search for biomarkers (for a detailed discussion see S. Fletcher-Watson & Happé, 2019). Whilst a need for early identification of biomarkers is commonly highlighted and favoured by autistic people and their families, the practical applications also need to be considered. The issues around identifying biomarkers in autism and potentially identifying autism pre-natal are often voiced by the autism community as a threat to eliminating autism (similar to other chromosomal disorders such as Down syndrome that can by identified prenatally). In addition, there are currently no evidence based early interventions available that could help to treat autism. Likewise, could an early brain scan remove a complex nuanced multi-disciplinary assessment of autism including identifying strengths?

Cognitive Theories of Autism

Many cognitive theories have emerged over the years within the autism research literature. Attempting to summarise all theories would be beyond the scope of this thesis, therefore the most influential cognitive theories will be discussed in the following section.

Theory of Mind

Theory of mind is the ability to infer the mental state and predict the behaviour of others (Premack & Woodruff, 1978). Late or no development of Theory of mind has been frequently suggested in autistic people and assumed that this directly underlies social deficits seen in autism (Happé, 1994). The classic test to assess Theory of Mind is the Sally-Ann false belief test (Wimmer & Perner, 1983). During the task the participants are presented with a scene in which one character (Sally) puts a marble into a basket and leaves the room. In Sally's absence Ann moves the marble to a box. When Sally returns, the participant is asked where Sally would look for the marble. If the participant understands Sally's false belief correctly (i.e. that it is different from the real state), then they would say Sally would look for the marble in the original location (in the basket where she placed the marble before leaving the room). While typically developing children at around the age of four master this test, and similarly children with Down Syndrome with the same mental age can correctly identify where Sally would look, 4-year old autistic children did not understand Sally's false belief (Baron-Cohen et al., 1985). It was posited that a lack of Theory of Mind abilities is linked to poor social abilities.

Although, the theory of mind tasks show some heterogeneity, more implicit measures (tasks that do not involve giving participants specific instructions and instead observe participant's spontaneous behaviour) support the notion that autistic adults show atypical theory of mind abilities. Senju and colleagues (2009) compared those with Asperger's Syndrome and non-autistic adults in an eye tracking experiment, investigating anticipatory eye gazes. In anticipatory looking investigations one directs the eye gaze at the location where they are anticipating an action. Senju et al. (2009) found that those pre-emptive eye gazes were atypical in autistic people. Whilst, the participants with Asperger's did not show this anticipatory eye gaze, behavioural performance was still accurate on the explicit theory of mind test. These findings were replicated in another study that used a paradigm with multiple trials (Schneider et al., 2013). This suggests even though theory of mind is thought to develop with age, anticipatory eye gazes are still atypical in adulthood in autism.

As non-autistic children passed the test at around 4 years, they reached ceiling effects and the false belief tests were further developed into second order mental state tests (e.g. Baron-Cohen, 1989, assessing the belief of another person's belief). Other variants of the task such as the Strange Stories (Happé, 1994, stories that involve i.e. sarcasm, lies and irony), Reading the Mind in the Eyes Task (presentation of black and white images of eyes in which participants have to label emotions), as well as the Awareness of Social Inference Test (McDonald et al., 2002, using video vignettes of conversations in which participants are asked to identify emotions) were developed to assess Theory of Mind. These studies have consistently indicated that autistic people have difficulties on these measures.

Whilst there is evidence to suggest that theory of mind in autism is atypical, there are however, several methodological and conceptual shortcomings. The theory has recently been refuted by several researchers who suggest that it perpetuates stereotypes in autism as theory of Mind measures are overly reliant on social communication, interaction and language abilities (Mathersul et al., 2013). In addition, Milton, (2012) argued that those tasks misrepresent typical bidirectional communication by just placing the emphasis on the participant and that it therefore represents an atypical social situation. The tasks aim to be ecologically valid, however, the task still requires abstract instructions and thinking (Mathersul et al., 2013). The theory of mind paradigms have also been criticised for requiring social competence and social understanding to pass the task, and the presentation of the tasks is of an abstract nature. These tasks also produce ceiling effects in the control group and therefore the direct comparison between autistic and non-autistic participants might also be artificial (Mathersul et al., 2013).

Weak Central Coherence

While Theory of Mind considers social aspects of autism, the other two major cognitive theories of autism primarily focus on non-social characteristics. The first of these has particular relevance for the present thesis as it considers information processing, cognition and attention in autism. Frith introduced the *Central Coherence* account in 1989 (Frith, 1989). Central Coherence is the ability to integrate visual information at higher order meaning or as a whole (e.g. Gestalt). The theory postulates that autistic people show a tendency to integrate the local features at the expense of the global coherence of an object or a scene (hence why the theory was later termed *weak central coherence*). The theory was based on findings that showed superior performance on task such as the embedded pictures task or Block design tasks requiring local processing. The embedded pictures task typically requires participants to identify a geometric target shape that is embedded in a line drawn object consisting of geometrical shapes (e.g. identifying a triangle in a scene or an object such as a pram). Performance was reported to be consistently more accurate and quicker compared to age matched peers for autistic children (Shah & Frith, 1993) and adults (Jolliffe & Baron-Cohen, 1997). Block design tasks (Kohs, 1920; Wechsler, 2011) require participants to match a one dimensional target pattern by assembling patterned, coloured blocks, likewise autistic participants showed above average performance compared to age and IQ matched non-autistic participants (Shah & Frith, 1993). Performance on these tasks were taken as evidence that autistic participants show a cognitive bias in their attention towards local information. Van der Hallen and colleagues (2015) conducted a meta-analysis with 56 articles and found that there was neither an enhanced local processing nor deficit processing global information. Reaction times were slower for the autistic participants at the global level especially when incongruent information was presented.

These tasks however, only require local processing, in other tasks that assess global and local features simultaneously, autistic people process information more accurately at a feature- based (local) level and perform equally well at a global level (Mottron et al., 2006). In addition, when Koldewyn et al. (2013) presented autistic and non-autistic children (mean age 8) with a free-choice local/global paradigm, autistic children indicated a preference for locally presented information but when asked to report on globally presented information they were able to report global information equally well than non-autistic children. This suggests that global processing is not impaired, but autistic people might show a preference for local information when given the choice.

It has been argued that weak central coherence is not unique to autism but has also been reported in other conditions such as Williams's syndrome (Farran et al., 2003) and a more global processing in Down Syndrome (Bihrle et al., 1989). A more recent cross-syndrome study with autistic children and children with Williams and Down Syndrome found that the patterns of local process were not consistent across tasks and global or local central coherence cannot reliably distinguish the groups (D'Souza et al., 2016).

Other variants of the weak central coherence theory have addressed the short comings and alternative theories such as the Enhanced Discrimination theory (O'Riordan & Plaisted, 2001) and Enhanced Perceptual Functioning model (Mottron et al., 2006). An alternative approach looking at increased perceptual capacity in autism (e.g. Remington et al., 2009) is discussed further below (see section on Perceptual Capacity in Autism).

Executive Dysfunction

The final theory that I will be presenting here has high relevance for this thesis, as it includes aspects of attention. Aspects of visual working memory and the role of executive attention will be further discussed in the subsequent section on attention. Here, I will focus on outlining the executive dysfunction theory of autism (Hill, 2004a; Pennington & Ozonoff, 1996). Executive functions are a collection of processes that serve goal directed behaviour such as decision making, self-regulation and planning; and encompass a range of top-down processes (Miller & Wallis, 2009). These processes consist of: inhibition, cognitive flexibility, planning and task switching (Denckla, 1996). The executive dysfunction theory (Hill, 2004a; Pennington & Ozonoff, 1996) proposed that autistic people show atypicalities in executive function. The underlying difficulties are thought to be related to processes in the frontal cortex. Executive dysfunction theory not only explains how the difficulties seen in executive function relate to repetitive behaviour, but also to social communication difficulties that are present in autism (Pennington & Ozonoff, 1996).

The original study by Pennington & Ozonoff (1996) reported that autistic people consistently report difficulties on executive function domains in tasks that involve planning as well as mental flexibility. The Tower of Hanoi task (sometimes also used as a similar variant called the Tower of London task) is one such task that measures planning abilities (Simon, 1975). In the Tower of Hanoi task, participants are presented with three pegs and a prearranged sequence of discs stacked on the peg on the left side. Participants are told to rearrange the disks to the right peg by moving the disks one at a time onto the pegs. However, larger disks cannot be placed onto smaller disks. Whether participants are able to complete the task successfully, the number of sequences needed to achieve the goal and sometimes the overall time that to complete the task is measured. To reduce the number of moves, efficient planning is required. The task difficulty can be manipulated by varying the amount of pegs and disks. Ozonoff et al. (1991) found that autistic children and adolescents were significantly less efficient in planning compared to their age and IQ matched counterparts. This suggests that autistic people have difficulties with their planning abilities. Olde Dubbelink and Geurts (2017) conducted a meta-analysis investigating planning abilities across 50 studies including participants across their life-span and found that planning is impaired in the autism group, regardless of age, IQ and task used. However, there is a considerable heterogeneity across tasks and methods employed, as well as a risk of publication bias with a reduced number of null findings (Olde Dubbelink & Geurts, 2017). Interestingly, there was also suggestions of performance being worse in an experimenter-administered task compared to a computer-administered version. However, these findings are not consistent, for instance (D. Williams & Jarrold, 2013) found no differences between the two versions of the task in autistic children.

Similarly, the Wisconsin Card Sorting task assesses mental flexibility and set-shifting abilities (Heaton, 1981). Participants are given a pile of cards that they have to organise onto stacks in front of them based on colour, quantity or shape of the objects presented on the card. The rules are not presented to the participants, the examiner indicates whether the cards were correctly placed. Thus, the participants have to work out the rules based on the responses by the examiner. The sorting rules change after a few correct trials and the participants have to adapt their card strategy accordingly. The task indicates overall completed set shifts, errors that result as either failure to maintain the set or perseverance on previous rules on the task indicates executive function difficulties. Landry and Al-Taie (2016) conducted a meta-analysis including 31 studies that used the Wisconsin Card Sorting task and found consistent impairments in the autism group compared to the non-autistic participants. However, the effect sizes reduced with age, which suggests developmental maturation in cognitive flexibility. The task variant, as well as whether the task was administered by a computer or human, was also not significant. Another meta-analysis summarising 75 studies that utilized a range of cognitive flexibility tasks however could not reliably differentiate between autistic and non-autistic participants across the tasks (Leung & Zakzanis, 2014). The study also indicated that the most sensitive test to differentiate between the groups was the Wisconsin Card Sorting task. This might not be surprising given that the task does not provide explicit task instructions which could result in difficulties for autistic participants trying to engage in the same way, and requiring a high degree of disengagement from the task , compared to when switching the rules (Leung & Zakzanis, 2014). Van Eylen et al. (2011) found that autistic participants performed equally well on cognitive flexibility tasks that have explicit task instructions and reduced task disengagement. However, performance is slower during task switching conditions and make more perseveration errors (an incorrect answer is repeated) and required less disengagement on the task and found that on control measures participants performed equally well as the control group. This indicates that the heterogeneity of performance might be task dependent. Therefore, it is debated how much cognitive flexibility is related to direct day-to-day inflexibility observed in autism (Geurts et al., 2009).

There are however some challenges with the executive dysfunction theory, mostly as the tasks cannot be defined by one executive function process such as cognitive flexibility, a task such as the Wisconsin Card Sorting Task also requires inhibition of previous rules and that this might be the reason why there is heterogeneity in executive function in autism (White, 2013). Task results are an artefact of the tasks and the instructions as the rules are open ended, inexplicit and often rely on social expectations (White, 2013). Therefore autistic people might misinterpret the task demands which therefore might lead to performance differences across the groups (Hill, 2004a, 2004b). In addition, difficulties seen on Wisconsin Card Sorting tasks are not unique to autism, and have been reported in conditions such as people with OCD (Shin et al., 2013) and those with clinical depression (McGirr et al., 2012)

Attention and information processing appears to be a crucial component in the theories outlined in this section and has been frequently highlighted in autism. Therefore, the next section will focus on attentional aspects in autism.

Attention

> "Millions of items of the outward order are present to my senses which never properly enter into my experience. Why? Because they have no interest for me. My experience is what I agree to attend to. Only those items which I notice shape my mind - without selective interest, experience is an utter chaos", James (1890)

In 1890, psychologist William James famously wrote "*everyone knows what attention is*" (James, 1890/2007). A recent article entitled "no one knows what attention is" counter argues that the concept of attention still remains elusive over a century later (Hommel et al., 2019). Yet, whilst the term attention is widely used, the definition is certainly still hotly debated (Carrasco, 2011). Research however has agreed that our capacity to process information is limited, each eye-movement would amount to an extreme flood of new sensory information therefore attentional processes are required to filter the information, attention is commonly thought to be a selective process in which a subset of information is prioritised for higher order processing (Carrasco, 2011; Posner & Petersen, 1990). Thus, attention is a fundamentally important cognitive process to efficiently process information and shape our experiences. Instead of one mechanism, a set of broad features of attention are related to alerting, prioritising, selecting and maintaining relevant information in the environment to achieve goal directed behaviour (Allport, 1993).These core attentional aspects can be broadly separated into sustained attention, selective attention and executive attention. The attentional core mechanism has been discussed across the literature and broadly proposed a separate neural network within the attention network theory (Posner & Petersen, 1990; Posner, 2012). In the following section I will review the core aspects of sustained, selective and executive attention separately. For each of the sections I will define the attentional mechanism, describe the behavioural tests that are typically used, and review the key evidence of the underlying neuroanatomical and -functional evidence before reviewing the typical development and subsequently review the related autism literature. The emphasis will be placed on selective and executive attention as these attentional mechanisms are most relevant to this thesis. Key theories that are pertinent to our current understanding of selective and executive attention will also be highlighted in the section below.

Sustained Attention.

Sustained attention is required when maintaining or achieving alertness or vigilance in expectation of a stimulus or an event (Posner, 2012). For instance, this is required when waiting for an announcement on a train to let you know that you are at the desired destination. Typically, the continuous performance task (Conners et al., 2003) or rapid serial visual presentations are used to assess sustained attention. In such tasks, stimuli are presented continuously and rapidly containing target information of higher and lower frequency that participants have to respond to; performance and attention lapses can be assessed over time.

Evidence for the anatomy of sustained attention comes from lesion studies which suggest that patients with lesions to the right frontal areas struggle to maintain and orientate towards the alerting stimuli. In particular this results in neglect to stimuli contralateral to the lesion (Molenberghs et al., 2009). In addition, the neurotransmitter noradrenaline is thought to be crucial to maintain or obtain alertness (Goldstein, 2006). Therefore, a region that is crucial for alertness is the locus coeruleus of the brainstem, as this is where noradrenaline is synthesised and released from the adrenal glands into the blood stream to achieve a state of alertness. In addition, evidence form fMRI data suggests that the right frontal and parietal cortex are involved in sustaining attention, in line with the lesion studies (Sturm & Willmes, 2001). In a recent study, sustained attention abilities over the lifespan were tested in a large-scale online experiment using a continuous performance task with real life stimuli (Fortenbaugh et al., 2015). Over 10000 participants completed the task and the study indicated that the sustained attention developed into adolescence, where from around the age of 15 strategies were developed and an age-related decline in sustained attention was shown from around 40 years.

Sustained Attention in Autism. The behavioural evidence for sustained attention is mixed, with most behavioural studies suggesting that there is no difference in sustained alertness in autistic children compared to non-autistic children (Keehn et al., 2010; May et al., 2013; Sanders et al., 2008). However, other studies such as Chien et al. (2014) found that using a continuous performance task, autistic children's (mean age 10) ability to sustain attention was impaired. In another study using a rapid visual information processing paradigm (Chien et al., 2015), autistic participants showed reduced sustained attention abilities, that were, however, moderated by IQ and age. It may therefore be that sustained attention matures with age and IQ. However, little is known about sustained attention in autistic adults. Murphy and colleagues (2014) conducted a cross sectional study with autistic and non-autistic adults and children. The study did not reveal behavioural differences on the task. Poor sustained attention on a continuous performance task was associated with less activation in inferior frontal cortical/middle frontal cortical, superior temporal, striatal, and lateral cerebellar attention. The activation in these regions increased in non-autistic participants but did not increase in autistic participants as a function of age, it was suggested that there was an atypical brain maturation in autism for sustained attention.

Selective Attention.

In this section, I will begin by outlining the definitions and theories that have been pivotal for our understanding of selective attention today. Subsequently, I will present key neuroanatomical and -functional findings and the developmental trajectory for selective attention before I review the literature on selective attention in autism.

Our capacity to process information around us is limited (e.g. Lavie, 2010; Vogel & Machizawa, 2004), therefore we require attentional processes to selectively attend to what we want to process (i.e. the task-relevant information) and do our best to ignore additional task-irrelevant distractors in order to achieve our goals. Selective attention is therefore responsible for prioritising and selecting sensory information for goal directed behaviour (Driver, 2001; Posner, 2012).

Selective Attention Theories

A famous example for selective attention is the cocktail party effect first described by Cherry (1953), in which he describes the ability to focus on one conversation despite a busy environment at a party where multiple people are talking simultaneously and additional conversations will be filtered out. The cocktail party effect inspired several early attention theories using auditory listening tasks. For instance, the *selective shadowing task* was one such task that was used to study early selective attention (Cherry, 1953). Participants listened to two spoken messages presented separately on headphones and had to attend to one message but ignore the other and repeat back the message that was attended to aloud (called "shadowing"). The results indicated when participants efficiently reproduce the attended message, they were unable to reproduce much of the content of the message presented on the unattended ear.

These findings led Broadbent (1958) to propose that there are two separate attention stages of information processing. The sensory input was first thought to be an extraction of the sensory and physical properties such as volume and pitch of the voices or the physical location and all of these physical properties could be processed in parallel. The second stage of the model that was thought to be responsible for abstract properties such as inferring the semantic information which is limited in capacity and could only process information in a serial manner. To prevent the capacity from overflowing, Broadbent (1958) proposed that a filter limited the incoming information (e.g. selectively attending to one of the two presented messages). Broadbent therefore proposed an *early section* theory suggesting that the distinction between attended compared to unattended information is made fairly early on and just physical properties of the unattended information are processed. However, other research has shown that information from the unattended ear can also be processed more deeply. For instance when someone says your name, you will be likely to hear it even if you were not paying attention to that person (Cherry, 1953). A number of other researchers tested the theory extensively and demonstrated using dichotomous listening tasks that semantic information is processed in the unattended ear (Moray, 1959).

As a result, the *late selection* theory was developed by Deutsch & Deutsch (1963). This theory postulates that instead of an early sensory stage all stimuli are being processed to the semantic level, and the filter then selects relevant information into conscious awareness (Deutsch & Deutsch, 1963). However, the theory was later refuted (Pashler, 1988; Treisman, 1969). For instance in one study, participants were asked to shadow one message in the target ear and manually tap when a target word emerged in either ear (discussed in Treisman, 1969). No differences in the frequency of detection of the target word would be expected if the late selection model was true, however an uneven response emerged in the tapping frequency (8% of the target words in the unattended ear and 87% in the attended ear). Therefore, the attention selection appears to be not entirely based on late selection Treisman (1964) came up with an account that combined the early and late selection, her *Filter Attenuation Theory*, instead of filtering out all unattended information in the early stages of processing, she proposed that an attenuator that weakens the information that is not attended (e.g. information presented on the unattended ear) and is still processed with less priority (Treisman, 1964). The theory extends the early and late selection accounts and helps to understand the conscious processing of visual information. The mechanism of the “attenuator” however did was not well defined and compared to the early and late processing theories the Filter Attenuation Theory received less attention, likely as the researchers in the field were divided in their views as to advocate for early or late selection (for a review on selective attention theories see Driver, 2001) .

While early selective attention work was focused on auditory attention, visual studies emerged in the following decades and one key theory the *Feature Integration Theory* by Treisman & Gelade (1980) proposed visual feature processing in selective attention. Across 11 visual search tasks Treisman and Gelade (1980) manipulated the visual features of the targets when visual features were defined by one single feature, reaction times were decreased and participants searched the features in parallel and the idea of the visual features being processed in a pre-attentive stage was put forward. However, when targets were defined by a combination of features ("conjunction targets"), e.g. shared the same colour or similar perceptual properties, reaction times were increased. Thus, participants searched the features serial and attention was required to bind the features together. This led the authors to conclude that feature maps such as colour, orientation or motion of the stimuli presented are processed pre-attentively. These features are bound together by attention as one coherent object. The theory is still highly regarded and a special issue was published in 2020 in the journal of Attention, Perception, & Psychophysics in honour of Anne Treisman's work (Wolfe, 2020).

Another influential theory, the *Load Theory of Attention and Cognitive Control* (henceforth Load Theory, Lavie, 2005, 2010; Lavie et al., 2004) is used as a framework to understand the mechanism of selective attention under different levels of load and has offered an alternative to the early/late selection debate. Load Theory recognises that there are both passive components (the amount of information you can perceive, termed perceptual capacity) and active components (the amount you can manipulate in working memory, termed cognitive capacity) of the selective attention process (see more details about the active component under cognitive load in the executive attention in the next section). According to Load Theory, at any given time we automatically use all our perceptual capacity to process information in an automatic and mandatory way, and our cognitive control processes are used to influence what information is prioritised. Load theory proposes a dissociation between distractor processing in situations of high perceptual and cognitive load. When a task exhausts our perceptual capacity because it contains a great deal of potentially task-relevant information (high perceptual load), we stop processing task irrelevant information. Thus, in this account the early and late selection debate is combined: early selection occurs under high perceptual load whereas late selection occurs when levels of load are low (Lavie et al., 2004).

In paradigms assessing perceptual capacity, participants typically perform two tasks concurrently: a primary visual search task and a secondary detection task (e.g. Macdonald & Lavie, 2008). On the primary task, participants must indicate which one of two possible target letters was presented. Perceptual load is manipulated by presenting up to five additional distractor letters in the search array. The secondary task requires participants to report whether an additional shape was present in the periphery of the search task or not (Macdonald & Lavie, 2008). Other commonly used paradigms are subitizing (rapid presentation of objects that require a number judgement without counting the objects) and multiple object tracking paradigms (tracking multiple moving objects simultaneously) to measure perceptual capacity using the framework of Load theory (Eayrs & Lavie, 2018; more on perceptual capacity and subitizing can be found in Chapter 4).

Selective Attention Processes

Selectively attending to the sensory environment can either occur as an overt action, by directing the eye movements towards the target, or covertly without any movement (Beauchamp et al., 2001; Posner, 2012). Attention can also be divided into endogenous attention, when attention is goal driven (top down, e.g. searching for someone with a red jacket in a crowd of people) and exogenous attention when attention is oriented towards external events in the environment (e.g. seeing a sudden movement of someone in a crowd, bottom up; Posner & Petersen, 1990). These control systems underlie distraction. Visual search tasks are often used to study selective attention, in which participants are ask to identify a target amongst additional distractors.

Early studies in the 80s have observed patients with unilateral spatial neglect and indicated that those patients showed an inability to engage with stimuli or information presented on the side contralateral to the lesion. Neuroimaging studies indicate that the difficulties patients with lesions presented in disengaging and shifting of attention is associated with the right temporal parietal junction as well as the superior temporal lobe (Karnath et al., 2001). Corbetta and Shulman (2002) suggested that there are two separate attention networks, for top down and bottom up attentional processes. The dorsal frontoparietal network is involved in top down attention and proposes that the main regions involved are the frontal eye field, the interparietal sulcus as well as the superior parietal lobe are involved in the pre-existing and goal oriented attentional processes. The second attentional network involves the ventral bottom up stream of attention that is activated when there are no prior expectations but relevant information is detected. Tasks that are particular relevant for the ventral stream of attention are oddball tasks (Donchin et al., 1978). Using such tasks, it was suggested that the core of the ventral attention network is the temporoparietal junction as well as the ventral cortex. The neurotransmitter acetylcholine has been proposed to be directly involved in attention and orienting of attention (Petersen & Posner, 2012). Recent studies for instance show that Acetylcholine is involved in the excitability of cells in the frontal eye field and therefore a key neurotransmitter for attentional control (Dasilva et al., 2019). The cellular activation is not yet fully understood, in a recent study Dasilva and colleagues (2019) found that Acyetylcholine changes the firing rate and affecting attention modulation in macaques through nicotinergic and muscarinic receptors. In addition, the role of the sensory cortex regions in the visual cortex has been highlighted in neuroimaging studies (Posner, 2012).

In line with the fMRI evidence of the involvement of the visual cortex, ERP studies indicate that visual search tasks where participants have to maintain fixation to the centre of the screen evokes a negative activation 180-300ms post stimulus presentation. This negativity is evoked on posterior electrode site areas contralateral to the side of the target presentation, termed N2pc (N2 posterior contralateral) and is thought to reflect deployment of spatial attention to possible targets (Eimer, 1996; Luck & Hillyard, 1994). Its amplitude changes with the number of targets and is therefore also a marker of capacity and has been used in the context of multiple object tracking (Drew & Vogel, 2008) and subitizing (Ester et al., 2012) as a marker for attentional saturation. The N2pc maker of spatial attention allocation will be used in Chapter 4 to identify capacity limits in a subitizing task for autistic and non-autistic adults.

To investigate the development of selective attention processes, visual search tasks have been successfully adapted for the use of 2-3 year old children and show gradual improvement over time (Scerif et al., 2004). Steele et al., (2012) found that visual search abilities improve steadily between 3-6 years, suggesting a linear development of selective attention abilities. Another study that included children from 6-12 years showed a steady increase in selective attention (Pozuelos et al., 2014). Children at the age of 6 showed the highest level of distractibility for incongruent information. Similarly, Lewis and colleagues (2018) tested children in groups of either 6, 8 and 10 years three times over 12 months and found that selective attention does not significantly change between the three groups, however there were significant gains between 6 and 7 years. This suggests that after 6 years of age, children have mature selective attention abilities. In addition, visual search was significantly slowed in early childhood and older adulthood, during a sample of 1920 participants aged between 6 and 89 years, conducting a general search task and a conjunction search task (Hommel et al., 2004). The reaction time followed a u-curve with reduced reaction times across search conditions for participants in their 20s and 30s. Children however showed high levels of distractibility in conditions that required filtering, especially in conditions without a target present and increased set sizes (Hommel et al., 2004).

Selective Attention in Autism.

In autism a contrasting picture has emerged regarding performance on selective attention tasks, with reports of superior visual performance yet increased distractibility. Importantly, previous studies have found that visual search performance is consistently improved in autism. Plaisted et al. (1998) found that 7-11 year old autistic children were quicker in a conjunction search task compared to non-autistic children. These finding were extended to autistic adults in which they showed improved visual discrimination abilities in visual search tasks (O'riordan, 2004). More recently, Kaldy and colleagues (2016) reviewed the visual search evidence across 22 experimental studies and found that the evidence consistently indicated improved search performance in reaction time and accuracy across varying numbers of distracting information and features. Other studies also indicated improved performance in autism: the embedded figures task (Shah & Frith, 1983), measures of abstract spatial reasoning including Raven's progressive matrices (Raven et al., 1998) and the Block design task a subtest of the Wechsler's IQ test (D Wechsler, 2011) have all consistently indicated improved performance in autism (Shah & Frith, 1993).

Crucially, the perceptual advantage observed in visual search and other perceptual tasks does not uniformly apply to performance across all visual perceptual tasks in autism. The improved performance in visual search tasks and visual discrimination abilities are in stark contrast with performance on other task where autistic people appear to be more distracted and have difficulties filtering out task irrelevant information from behavioural (Christ et al., 2007; Remington et al., 2009) as well as neuroimaging studies (Keehn et al., 2016; Ohta et al., 2012). It is therefore unclear how attention is captured in autism given the contrasting performance in visual perceptual tasks. Several hypotheses have been postulated in the literature to explain the contrasting observations of attention capture in autism. Previous accounts have hypothesised: 1) over focused attention that has a too narrow attention spotlight, 2) an over-focused attention for task relevant features in which features that share similar properties to the target are processed (increased top-down processing) or 3) an inefficient focus or filter. Each hypothesis will be discussed in more detail.

Lovaas et al. (1979) postulated that autistic people focus on one object and disregard other objects completely, suggesting a narrow attention spotlight. Evidence for a narrow attention spotlight also comes from research with children and adults using oddball tasks, where autistic people show reduced sensitivity to atypical and novel stimuli (Clery et al., 2013; Sokhadze et al., 2017). This hypothesis was also supported by other findings, for instance Robertson and colleagues (2013) used a visual spatial cuing paradigm, autistic and non-autistic adults focused on a central fixation cross and were presented with a peripheral target stimuli and a distractor in varying spatial distances from a spatial preceding cue. Autistic participants' performance was improved when the targets were presented closer to the cue indicating a sharper gradient in their attention lens. However, other research has indicated improved performance on task when additional information was processed outside of the central task focus (Remington et al., 2012, this will be further discussed under Perceptual Load in Autism).

An alternative account to the narrow attention stoplight hypothesis was developed, suggesting an increased focus on an attention capture of task features that is shared between the target and distractor information. As such, when a target consists of a certain colour, other distracting information is only processed if it shares the same defining features of the target (relying on top-down processing e.g. Folk & Remington, 1998). If the processing of such a task feature captures increased attention, this could be taken as evidence that a more top-down modulation is used. Likewise, attention capture for irrelevant information was shown to increase when the irrelevant information shared features with the target information, indicating a reduced modulation of bottom-up signals (Keehn et al., 2016).

Interestingly, Brian et al. (2003) showed in a visual priming task a facilitation effect in a group of autistic participants (age range from 7-33) when a target shared the colour feature with the distractor; the same top-down facilitation was not found in the non-autistic sample.

Similarly, Greenaway and Plaisted (2005) tested top-down attention modulation across two experiments in children (mean age 11 years). In a spatial cuing paradigm and visual search task top-down modulation for coloured cues facilitated attention capture for autistic and non-autistic children, but an onset cue was significant for the non-autistic participants only. This suggests that top-down attention capture might be stimulus specific in autism.

More recent studies by Keehn and colleagues did not replicate these behavioural findings in autistic and non-autistic participants (Keehn et al., 2016, 2017). In a rapid serial visual presentation paradigm, participants had to respond to targets (digits) that were presented in red and indicate in a forced response option, whether the digit presented would be classed as a low or high digit. Alongside the target, flanking task irrelevant digits were presented in either grey, matching the target colour, or a non-target matching colour (green). Increased error rates would be expected when the target is presented alongside the distractors that share the same colour feature. Unexpectedly, the participants in both groups (mean age 14, 12-17 years) showed reduced reaction times for the conditions where the distractors were presented in colour and reaction times were higher in conditions where the distractor was presented in grey. The authors suggest that this might be related to the participants' age. However the recorded fMRI data, suggests a reduced target activation in the right-lateralized ventral network (bottom-up network) and more specifically in the right temporal-parietal junction. The authors conclude that this suggests a reduced bottom-up modulation in the autism group. Similarly, accompanied suggest that alpha band activation, associated with attentional capture, shows reduced desynchronization 400-700ms post stimulus onset in autistic compared to non-autistic children. Together, the authors' conclusions indicate a reduced bottom-up modulation and differences in attention capture effects in autism.

The mixed behavioural findings however do not support any conclusions as to whether attention capture might be impaired due to an over focus of shared features of targets and distractors (top-down) or bottom-up modulation. However other theoretical accounts such as a Bayesian based account in autism (Pellicano & Burr, 2012) posit that sensory processes are less dependent and prior experiences and knowledge when interacting with the world (top-down processing) but rely on the saliency of information within the sensory environment (bottomup processing).

Lastly, Burack (1994) hypothesised an inefficient attention lens and issues in filtering between task-relevant and -irrelevant information in autism. More recently EEG evidence has supported the hypothesis and suggestions of alpha band activation showed that autistic adolescents had a reduced suppression of task irrelevant information during a visual and auditory cuing paradigm (J. W. Murphy et al., 2014a). Similarly, Milne and colleagues (2013) found a correlation between autistic traits and a reduced differentiation of targets and non-targets in a visual search task, evidenced by the ERP component P3b. Together these findings are in line with the proposals of an overly broad attention lens, which leads to inefficient visual attentional filters (Burack, 1994).

These explanations for an over focused or a too narrow attention lens and reduced filtering abilities in autism are not thought to be mutually exclusive, one approach that brings the evidence of a wide and narrow attentional lens together is an increased perceptual capacity in autism (e.g. Remington et al., 2009). This is particularly relevant for this thesis and will be discussed in detail in the next section.

Perceptual Load in Autism. As previously highlighted, the autism literature has shown a striking contrast between studies that suggest that autistic people have an increased attentional lens and are more distracted by task irrelevant information (e.g. Murphy et al 2014a) but also have overly focused attention and show superior selective attention abilities on other tasks (Plaisted et al., 1998). In particular, Remington and colleagues (2009; 2012) found that autistic individuals are able to simultaneously process more visual information at a given time on paradigms such as described in the context of the Load theory e.g. Macdonald and Lavie (2008). This can lead to more effective search performance but may also increase one's propensity to process and attend to additional task-irrelevant information in the environment. In previous studies, autistic participants' ability to detect the secondary stimulus was constant even when the number of distractors presented in the primary task increased. Conversely, for non-autistic participants, secondary task performance decreased as the perceptual load of the primary task increased (e.g. Remington et al., 2009; Remington et al., 2012). This suggests that autistic participants have increased perceptual capacity, i.e. they are able to perceive more perceptual information at any given time. Support for this also comes from recent ERP research. Across two studies, Dunn et al. (2016) found that participants with high autistic traits showed an increased N2pc compared to those with low autistic traits suggesting an increased perceptual capacity. The evidence however also points to decreased distractor suppression as measured on the P_D.

Interestingly, a fMRI study that manipulated perceptual load in autistic and non-autistic adults indicated that there were no group differences in attentional networks, however the autism group showed reduced activation in visual cortical areas and interparietal cortex indicating a reduced load dependent modulation (Ohta et al., 2012). This suggests that the differences seen in selective attention differences may be related to sensory processing areas.

The increased perceptual capacity is beneficial in tasks such as the dual visual search paradigm outlined above, but it may also lead to increased levels of distraction in other tasks. To reiterate, the findings can be directly applied to the Load Theory (Lavie, 2005, 2010; Lavie et al., 2004), all perceptual resources are used to process information in an automatic and mandatory way. If perceptual capacity is not filled with task relevant information, the excess capacity will be used to process task irrelevant information, leading to increased levels of distraction, this could therefore explain the contrary literature in selective attention in autism (e.g. the observed narrow attention vs a wide attentional focus). The presence of increased perceptual capacity has been demonstrated for autistic children and adults (Swettenham et al, 2014) in visual (Remington et al., 2009) and auditory domains (Remington & Fairnie, 2017), however the overall capacity limits and neurophysiology of perceptual processes are not yet fully understood (Hessels et al., 2014). In Chapter 4, I will explore ERP markers of selective attention (N2pc) to explore perceptual capacity limits in autism further. Another question that still remains is whether autistic people’s ability to process more information is also seen for other components of selective attention such as visual working memory availability and/or capacity, this will be the focus of the next section on executive attention (and visual working memory).

Executive attention.

A number of accounts have previously addressed attentional mechanisms in executive function tasks. Executive function (as previously introduced under cognitive theories of autism) is an umbrella term for processes involved in planning, updating, switching and maintaining information. Whilst most accounts posit that executive attention serves goal directed behaviour and is a capacity limited resource (Baddeley, 2011; Vogel et al., 2005), the theories differ on the executive construct that executive attention serves (for a review see Tiego et al., 2020). For instance, the attention network theory assumes that executive attention is related to inhibitory tasks such as Flanker tasks and detecting and resolving conflict in congruent and incongruent information (e.g. Petersen & Posner, 2012). Other accounts suggest that measures of working memory capacity (the amount of information that is perceptually unavailable that can be simultaneously maintained) is a domain general measure directly associated with attention (Kane & Engle, 2002). Where a central system such as the *central executive* is recruiting and prioritising information in working memory (Baddeley, 2011; Baddeley & Hitch, 1974, more on working memory capacity and the central executive in the section on working memory below).

The integrative model of unity and diversity suggests that there are common executive and unique mechanisms (Miyake et al., 2000). An attentional control mechanism is thought to serve three separate executive function mechanisms for first order processes on inhibition (control automatic prepotent actions and cognitive processes), working memory (updating and monitoring of information) and shifting (switching between cognitive processes and tasks) of information is responsible for lower level cognitive processes and behaviour (Conway et al., 2008; Miyake et al., 2000). Recent research based on hierarchical factor models, genetic and correlational studies suggests that these three core executive functions are highly correlated but separate mechanisms (Friedman et al., 2008; Gustavson et al., 2015; Miyake et al., 2000). Thus, executive functions are thought to share common features (unity), but were also separable in the mechanism (diversity). Whilst the mechanism of executive attention is still debated, for the purpose of this thesis I will explore executive attention on the three unity subdomains of: inhibition, shifting and working memory separately in the following section.

Inhibition.

Inhibition is an act of ignoring or supressing thoughts, task-irrelevant actions to achieve goal directed behaviour. In daily life, inhibition could occur when having to change a daily route to pick something up from the supermarket. Inhibition is multidimensional and can be emotionally (“hot” executive function, e.g. stopping oneself from eating a marshmallow) and non-emotionally charged (“cold” executive function, e.g. stopping oneself from pressing a button in a task). For this introduction section I will focus on the non-emotional inhibition task, as these are relevant for the thesis (for a review on emotional inhibition see Traue et al., 2016). As such, cold executive inhibition is often assessed on tasks that require a suppression of motor responses (prepotent inhibition where an automatic, initiated motor response has to be stopped. For instance, a Stroop task is commonly used, in such tasks a word list of written colours is presented to the participants, reaction time differences are compared on trials were the written word matched the colour it is printed in (congruent trials) or differs from the ink it is printed in (incongruent trials) when labelling the colours of the ink and not the word (inhibiting the response to read the word, Stroop, 1935), or a Go/no-go task where participants have to continuously respond to a target and withhold their response on trials were a stop sign is presented prior to the stimulus (Lappin & Eriksen, 1966). Another example of cold executive inhibition is referred to as interference control or cognitive inhibition (e.g. ignoring incongruent information). This is typically assessed in a Flanker task (Eriksen & Eriksen, 1974) in which participants are presented with a central target (e.g. an arrow that either points left or right). The central arrow is flanked by further arrows that either point into the same direction as the central arrow (congruent) or into the opposite direction (incongruent). Participants have to indicate the direction that the central arrow points to as quickly and accurately as possible and conflict monitoring is assessed on trials were participants are inhibiting the flanking incongruent arrows. The congruency reaction time effects (subtracting mean reaction times for congruent from incongruent trials) typically helps to assess efficiency scores (large scores indicate ineffective conflict monitoring).

Studies using fMRI have found that the anterior cingulate cortex as well as the inferior, middle and superior frontal gyri and inferior and superior parietal lobule are involved in inhibitory tasks (e.g. Nee et al., 2007). The pre-frontal cortex maturation is also thought to be pivotal for developmental advances in prepotent and interference control. Williams et al (1999) found that prepotent inhibition develops on a go/no-go task as around 3-4.5 years and a stop task from around 7 years. In a stop task, participants have to respond to a target item and if a sound is played in conjunction with the target they have to inhibit the motor response and not respond to the target. The task is thought to be more challenging than a go/no-go task as an active motion has to be stopped. Both tasks result in a U-shaped development curve, indicating reduced performance from mid adulthood. Another more recent study (available as a pre-print) however, tested toddlers on an adopted version using a touch screen task where they have to respond to a target that can appear in two different spatial positions (Holmboe et al., 2019). Using a cross-sectional and longitudinal design, the study indicates that inhibitory control develops between 16 and 24 months and the task is suitable for toddlers from 10 months of age. Results across the lifespan indicate that the task follows the same u-shaped curve with reduced inhibitory control from around 40 years of age.

Inhibition in Autism.

In this section I will explore the attentional difficulties related to conflict monitoring and inhibition within the autism literature. The increased reaction time cost (also referred to as congruency effect) on inhibitory tasks such as Flanker task between incongruent and congruent trials has been proposed as a marker for inhibition in autism (Fan et al., 2005).

Overall, autistic children and adolescents are thought to have difficulties inhibiting. This was confirmed by Geurts and colelagues (2014) who conducted two separate meta-analysis including 47 studies on pre-potent and cognitive inhibition, with predominantly autistic adolescents and children. The study found that autistic participants showed differences across groups suggesting greater difficulties with interference in autism. On tasks that require a suppression of motor responses (prepotent inhibition) e.g. on a Stroop or Go/no-go task, autistic participants showed greater effect sizes (*d*=.55) compared to tasks that required interference control (*d*=.31; e.g. ignoring incongruent information in Flanker tasks). Additionally, the effects were moderated by age for pre-potent inhibition but not for cognitive interference control tasks. As the study largely focused on children and adolescents, did not resolve whether inhibitory difficulties remain in adulthood. However, a recent large scale project has shown that the difficulties also occur in adulthood, and that diagnostic status or measure of autistic traits predicted the level of inhibitory control deficits on a go/no go task (Uzefovsky et al., 2016).

Other small scale studies do not show behavioural evidence of reaction time or accuracy during inhibition tasks in adulthood in autism, however, neural correlates appear to be altered. As such when testing autistic adults on a Stroop, Go/no-go task and task switching task, autistic adults' behavioural performance did not differ compared to non-autistic adults (Schmitz et al., 2006). Similarly, Langen et al. (2012) found differences in overall correct responses on a Go/no-go task but no reaction time differences. Importantly both studies reported differences in brain activation: e.g. Schmitz et al. (2006) found that the activation of the left inferior and orbital frontal gyrus, and the left insula and parietal lobes was increased in autistic participants despite no behavioural differences, suggesting that an increased cognitive effort is required in autism. This could be related to evidence suggesting that overall alpha oscillation, associated with control mechanisms, is also reduced during response inhibition during a Go/no go task in autism (Yuk et al., 2020). Both, Schmitz et al. (2006) and Yuk et al 2020) did not find group differences at a behavioural level in the autistic and non-autistic adults, these findings are in contrast with behavioural findings from the large scale study, indicating behavioural differences (Uzefovsky et al., 2016). As such, inhibitory functions at a behavioural level are only partially understood. It might be that autistic people require more cognitive resources to achieve the task, or it may reflect the heterogeneity observed in the executive dysfunction literature.

In addition, the performance monitoring literature supports the evidence of altered cognitive processes during inhibition in autism. To achieve correct performance on inhibitory tasks such as Flanker tasks, behavioural responses have to be monitored. South et al. (2010) tested the related ERP markers for error monitoring (ERN) associated with conscious processing after an error on an inhibition paradigm (Gehring et al., 1993). The ERN was attenuated in autistic participants compared to an age and IQ matched control group. The authors suggest that this reduced neural post error response may show that autistic participants have a reduced sensitivity to errors but this could also show an inflexibility to adjust their behaviour accordingly and therefore indicate reduced inhibitory control in autism. Inhibition will be particularly relevant for chapters 2 and 5 of this thesis.

Shifting of Attention.

Attention shifting is concerned with switching attention between tasks, sets or (mental) operations and it is also sometimes referred to task switching and is thought to be a core mechanism of executive attention. As previously described in the executive dysfunction literature (see section on cognitive theories in autism), the Wisconsin Card Sorting task is a commonly used paradigm to assess task shifting. As outlined previously, given the high levels of referential ambiguity of the rules of the Wisconsin Card sorting task such *context* dependent tasks may lack validity in autism. Thus, other tasks requiring *response* switching might be more useful to accurately assess task switching. In such tasks participants are presented are presented with two sets of instructions (cues) that have two different rules for subsequent stimuli that they are presented with (hence why the paradigm is sometimes referred to as cued task switching). This can for instance be two objects with different shapes and colours, requiring the participants to either report on the shape of the object or the colour of the object by pressing one of two dedicated buttons on the keyboard. Participants have to make decisions on a trial by trial by trial basis to respond according to the cue they are presented with. Behavioural performance on trials where instructions are shifted, results in increased reaction times (e.g. the switch cost). This paradigm will be used in Chapter 5 and is therefore most relevant to this thesis, and I will focus on the finding using response switching (or also known as cued task switching) paradigms in this section only.

Whilst the frontoparietal network is thought to be involved in domain general task switching, cued task switching is more specifically associated with activation in the posterior parietal cortex and the inferior frontal junction (Kim et al., 2012). In a cross-sectional study Zheng and Church (2021) tested children (aged 8-16 years) and adults on a cued task switching task with concomitant eye-tracking. Overall, children spent more time focusing on the cue rather than the response choice they were presented with. This suggests that either children are taking longer to apply the rules or the interpretation of the rule itself takes longer. Further analysis suggests a maturation throughout adolescence, with 14-16 year olds showing similar eye tracking and response patterns to adults. However, the group of 11-13 year olds show tentative signs of eye movement development, with only partially developed behavioural adaptations. It must be noted however, that task switching paradigms are highly dependent on inhibition of the previous rule and visual working memory (maintaining the task instructions throughout the trial).

Attention Shifting in Autism.

Reaction time costs in task switching trials have consistently shown that autistic people have difficulties shifting attention. For instance, findings from fMRI studies indicated that autistic young adults showed increased task switching costs compared to non-autistic participants. In addition, the severity of restrictive and repetitive behaviour was associated with reduced BOLD activation in anterior cingulate and posterior parietal regions during the task compared (Shafritz et al., 2008). Similarly, a recent large scale fMRI study with autistic and non-autistic adolescents (n= 141 with a mean age of 17 years) indicated that when task conditions must be switched in response to a previously presented cue, autistic teenagers recruit more networks and show larger reaction time costs (Gordon et al., 2020).

Interestingly, Biro and Russell (2001) suggest that arbitrary presentation of the trials might contribute to some of the difficulties in autism. However, this was implicitly tested in a more recent study with autistic adults using a voluntary task switching paradigm, where there is no external cue and participants are required to indicate which rule they are following at the beginning of each trial (by pressing a button on the keyboard, Poljac et al., 2017). Autistic adults show reduced cognitive flexibility which was directly related to behavioural flexibility (the number of rule changes) compared to non-autistic adults (Poljac et al., 2017), proving that difficulties are also observed when the rules are set by the participants themselves.

Visual Working Memory.

To successfully navigate the world around us we have to maintain and manipulate information that is no longer perceptually available, and to do so visual working memory is required (Berggren & Eimer, 2016; Konstantinou & Lavie, 2013; Luck & Vogel, 2013). Maintaining visual working memory for a short period of time is therefore a crucial cognitive ability for goal directed behaviour.

Divisions between a fragile and fluctuating primary storage (short-term memory) and a concrete secondary storage (long term memory) were proposed early on, with proposals for a distinct storage between short-term and long-term representations (Atkinson & Shiffrin, 1968). The domain general storage model suggested by (Atkinson & Shiffrin, 1968) proposed that after sensory information was processed through active rehearsal or chunking of information presented in short term memory, the storage system acted as a transitional store from which information was consolidated in the long-term memory. The assumption was that holding information in the visual working memory would guarantee transfer to the long-term memory. In addition, deficits in short-term memory would also be reflected in long-term memory. Lastly, short-term memory was said to be required for long-term memory consolidation. The assumptions of the multicomponent model of the "all or nothing" approach was later disproved (e.g. Baddeley & Hitch, 1974).

Based on experimental working memory paradigms, Baddeley and Hitch (1974), in their seminal paper, proposed a dynamic model of visual working memory[2] processing. The theory included three integrated subsystems, limited in capacity. In this hierarchical model the central executive oversees two subsidiary systems responsible for processing semantic and visuospatial information. The central executive in the model provides the attentional control. The phonological loop is responsible for maintaining verbal information of speech perception and speech production in mind, whereas the visual spatial sketch pad is used to maintain and manipulate visual and spatial storage information. In 2000, Baddeley proposed a fourth component, the episodic buffer, a module that deals with temporal information, conscious awareness and reflection on information across space and time (Baddeley, 2000).

Other related perspectives to Baddeley's work focused on neural substrates of visual working memory (e.g. Fuster, 2015; Fuster, 2000). The neural mechanism of visual working memory maintenance is associated with the lateral pre-frontal areas as established in foundational work on visual working memory based on lesion studies of non-human primates and white matter tract evidence (e.g. Goldman-Rakic, 1995). For instance, early studies using single cell recordings of non-human primates' pre-frontal cortices have largely contributed to our knowledge about the involved in the field (Fuster & Alexander, 1971). The monkeys were trained to perform a task in which each trial consists of a set of visual stimuli that form a memory array followed by a short delay and the test array. In the test array, on half of the

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[2] Note. The term *short term memory* is historically been used to define a transient storage that only requires maintenance without further manipulation based on Atkinson & Shiffrin (1968)'s work (as defined in the framework of Load Theory, e.g. Konstantinou & Lavie, 2013; Lavie, 2005). However, more recently the terms visual short term memory and visual working memory have been used interchangeably. Thus, throughout the thesis I will use the term visual working memory to refer to processes of visual maintenance to align theories and relevant literature.

trials there is a change in one of the stimuli presented (i.e. delay match to sample task or change detection task, Fuster & Alexander, 1971). The recording of the single cell neurons in the prefrontal cortex and mediodorsal nucleus of thalamus indicated an increased activation during the delay period, suggesting that those areas are involved in maintaining visual information (Fuster & Alexander, 1971). With increasingly advanced neurophysiological methods, later fMRI and MEG studies suggested that other regions such as the posterior parietal and the inferior temporal cortices are involved in spatial and object information processing respectively and in direct reciprocal interaction with the prefrontal cortex. Importantly, mnemonic representation is thought to be mediated by sensory areas in the visual cortex (D'Esposito et al., 1995; Ester et al., 2010; Serences et al., 2009). When participants were asked to maintain visual information while in an fMRI scanner, the primary visual cortex (the V1) and a sustained activation in the intraparietal sulcus were observed. This was associated with the visual maintenance period and sensitivity to the varying amount of information presented, to be retained during a memory array (Serences et al., 2009; Todd & Marois, 2005). Thus, these neural correlates are thought to be related to visual working memory load, and crucially indicate a person's working memory asymptote.

Further evidence for the involvement of sensory regions for visual working memory maintenance stems from EEG studies. Analogous to the task used in non-human primates, change detection tasks are also used in humans to assess visual working memory and allow estimation of capacity limits (Luck & Vogel, 2013; Vogel & Machizawa, 2004). A lateralised change detection tasks (with presentation of stimuli on both sides of the screen; see Figure 1a), was used to investigate the ERP component called contralateral delay activity (CDA; also known as sustained posterior contralateral negativity, SPCN) as a component reflecting the maintenance process of visual working memory. The CDA is an enhanced and sustained negativity elicited over posterior brain areas during a retention period, contralateral to the side of visual space where to-be-memorised information was previously presented (Luck & Vogel, 2013; Vogel & Machizawa, 2004). This negativity typically persists during a maintenance period, and also increases in size in line with the number of items currently being maintained in memory, reaching a maximum amplitude or asymptote at around three to four items and corresponding to individual differences in visual working memory capacity (Unsworth et al., 2014; Vogel & Machizawa, 2004). Thus, the CDA component can be considered a marker of visual working memory rehearsal as well as an online neural measure of individual differences in visual working memory capacity. Crucially, has also been a marker in successfully distinguishing between people's behavioural markers of visual working memory capacity and their neural performance. In Figure 1b, the CDA difference wave is contrasted for those who behaviourally demonstrate a higher visual working memory capacity compared to those who have a lower capacity. Importantly, those who show lower rates of visual working memory capacity, the task irrelevant information in the display is not sufficiently filtered out, and instead is treated similarly to the high load condition where four task relevant information are presented. Whereas the participants with higher working memory capacity filter out the irrelevant information and processed the task relevant information more similarly to the low load condition, when only two task relevant stimuli were presented. Therefore, the CDA also allows the investigation of filtering efficiency in visual working memory and is thought to be directly linked to behavioural markers of visual working memory (figure 1c; this paradigm and the ability to assess neurophysiological markers of CDA including visual working memory capacity and filtering efficiency will be discussed in more detail in Chapter 3 and Chapter 4).

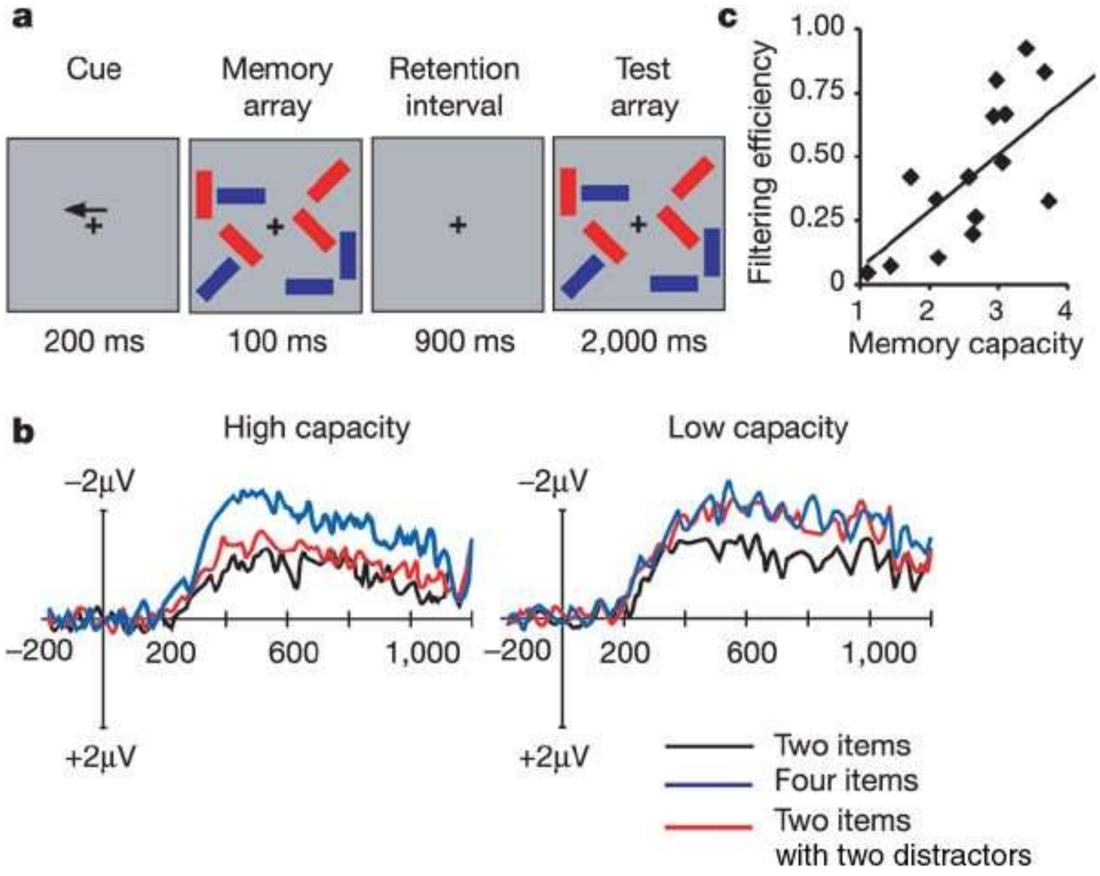

Figure 1. a) depiction of a change detection trial with task relevant and irrelevant information, b) Difference wave of CDA activation for high and low capacity individuals, indicating an increased distractor processing of distractor items in the participants with low capacity compared to participants with high capacity, c) positive association between memory capacity and filtering efficiency, retrieved from Vogel et al., (2005).

Interestingly, the findings based on visual working memory capacity are in line with proposals made by Load Theory about visual working memory capacity. The capacity limits for visual perceptual processes (i.e. perceptual load) and visual working memory are believed to be similar, at around three to four items, and involve similar mechanisms (Emrich et al., 2009; Konstantinou & Lavie, 2013). Furthermore, Konstantinou and Lavie (2013, experiment 1) tested participants on perceptual tasks as well as visual working memory maintenance (e.g. visual working memory load). The tasks consisted of dual task paradigm, in each trial participants had to memorise coloured squares that were presented in a change detection task, during the retention interval participants completed a visual search array in which a target letter (X or N) had to be detected with a masked shape that was presented in the periphery. Subsequently, participants were presented with the test array of the change detection task and had to indicate whether there was a change or no change. Load was manipulated in the perceptual load condition by increasing the distractor items in the visual search array, whereas in the visual working memory condition, the set size of the objects which were to be remembered was increased. The study indicated that participants' ability to detect the additional shape in the periphery was reduced in both conditions under high levels of load. The results indicated that with increased load (number of objects to maintain at any given time) in the visual working memory task, participants had no available capacity to process the additional information Thus, the authors argued that distractor processing decreases with visual working memory load, similar to perceptual load. Visual working memory maintenance and perceptual load, the shared visual resources for perceptual information are within the same visual cortical areas and influence the likelihood that distractor information will be deeply processed to begin with. Indeed, as previously outlined, other studies indicate the maintenance of information in visual working memory involves sensory recruitment and active rehearsal within the sensory areas of the occipital cortex, (outlined in more detail in chapter 3; Bruning & Pratte, 2017; D'Esposito & Postle, 2015; Ester et al., 2010).

The development of visual working memory is thought to mature through childhood, whilst 3 year olds are thought to have a capacity limit of 1.5-2 items, 7-year olds have been shown to maintain 4 items in visual working memory (Simmering, 2012). Cortical networks are thought to mature throughout childhood, for instance a neuroimaging study showed that the connectivity between the areas was more connected in 4 year olds compared to 3-year olds (Buss et al., 2014). The parietal activation was also increased in 4-year olds and is thought to show more robust sensitivity to load manipulations. A cross-sectional fMRI study with children, adolescents and adults indicated that the connectivity increases and becomes more localised in adulthood (Geier et al., 2009). This suggests maturation of the cortical areas for visual working memory during early adulthood. Yet, studies suggest both changes across adulthood, revealing an age related decline on the CDA (e.g. Störmer et al., 2013), as well as that age related differences do not occur (Schwarzkopp et al., 2016). This might be because cognitive ability remains heterogeneous at older age and recent studies have investigated age related differences on the CDA in cross-sectional studies only, not using longitudinal paradigms.

Visual Working Memory in Autism.

In recent years, meta-analyses have been published assessing executive function and visual working memory (Demetriou et al., 2017; Kercood et al., 2014). These reviews suggest that there is a visual working memory deficit for autistic people (Habib et al., 2019; Kercood et al., 2014; Wang et al., 2017) when combining evidence of performance on visual spatial attention tasks such as n-back tasks (continuously updating and comparing the presented information to previous trials, Kirchner, 1958), Corsi Block Tapping tasks (remembering a sequence of blocks and "tap" the blocks in the order that they were presented in; Corsi, 1972) or the CANTAB visual working memory battery (range of neuropsychological tests including a delay match to sample test Sahakian & Owen, 1992). However, these tasks typically involve further executive functions such as set shifting, updating and inhibition of information and would typically engage the prefrontal cortex and not recruit visual sensory cortex activation. In addition, oddball tasks (that were previously discussed in the section aetiology of autism) are also sometimes referred to as change detection tasks (Cui et al., 2017), however, these tasks offer an understanding of novelty processing and are not a direct measure of working memory capacity and visual maintenance. A few studies have investigated attentional processes in autism using change detection with real life stimuli (e.g. Burack et al., 2009; Fletcher-Watson et al., 2006). These tasks typically follow the same principle as the change detection tasks detailed above, where participants are presented with one or two pictures of real-life objects and then have to indicate whether there is a change in colour, orientation or deletion/edits of a part of the object (Ashwin et al., 2017; Vanmarcke et al., 2018). Some studies investigate the performance of changes that are central to the picture or marginal or contextually congruent or incongruent, inverted or upright (Vanmarcke et al., 2018). Given the heterogeneity of tasks and differences in exposure times, social vs. non-social nature of the stimuli, response options (verbal or button presses on a keyboard), it might not be surprising that the results in the literature are varied.

In addition, the findings using real life change detection images are mostly based on autistic children. As such, Burack et al. (2009) reported no differences in performance for children overall however non-autistic children improved with age, but autistic children seemed to follow a modulated developmental trajectory. However, other studies with autistic children indicate superior performance compared to non-autistic adults in change detection task with real life objects (Fletcher-Watson et al., 2012). Another recent study testing autistic adolescents suggested that memory performance was similar to age and IQ matched non-autistic peers and better for information presented inversely (Vanmarcke et al., 2018). Fletcher-Watson et al. (2006) did not find any differences between young autistic adults and non-autistic adults.

Whilst it is important to study more ecologically valid tasks, the fundamental aspects of visual working memory such as assessing capacity limits using standard change detection tasks remain largely unexplored in autism. Ozonoff and Strayer (2001) investigated visual change detection with 1, 3, and 5 stimuli in autistic and non-autistic children and children with Tourette syndrome and did not find any group differences in accuracy and reaction time (visual working memory capacity using markers such as Pashler K (Pashler, 1988) were not assessed). To the best of my knowledge there are only two studies investigating visual working memory capacity using a standardised change detection task in autistic adults. Remington (2009) reported no group differences in performance for autistic and non-autistic adults on a change detection task with a single object probe. In addition, in a recent study Bodner et al. (2019) presented participants with objects with a high and low chance of occurrence in a single probe change detection task. Eye tracking data suggested that the autistic participants use different strategies compared to non-autistic participants, and that young autistic adults in the study showed increased processing of task irrelevant information. However, it is questionable whether the differences found in the strategies were a result of the implicit nature of the instructions rather than inefficient memory allocation. Single object probes for the test array might be confusing for autistic people, as they may take the instructions literally as there will always be a change from the memory to the test array with a single probe. In addition, the exposure time for the memory array (of 1500ms) was increased compared to standard change detection tasks (around 500ms). To date, there are no studies available that assess visual working memory capacity in standardised tasks using behavioural and electrophysiological markers in autism. Moreover, studies have not yet examined whether filtering efficiency analogous to distractibility in perceptual tasks applies to visual working memory tasks in autism, this will be addressed in Chapter 3 and 4 using electrophysiological markers of CDA to assess visual working memory capacity and filtering efficiency.

Cognitive Load.

To reiterate, according to Load Theory, at any given time we automatically use all our perceptual capacity to process information in an automatic and mandatory way, and our cognitive control processes are used to influence what information is prioritised and minimises intrusions of irrelevant information. Importantly, Load Theory proposes a dissociation between distractor processing in situations of high perceptual and cognitive load. As previously outlined (see selective attention and visual working memory), when a task exhausts our perceptual capacity because it contains a great deal of potentially task-relevant information (high perceptual load), we stop processing task irrelevant information. Conversely, a task that requires high cognitive load (i.e. involves multiple demands such as memorising a digit string while performing a visual search task) the ability to prioritise targets and block out distractors is diminished, and increased distractor processing is observed. This more active component of attention will be explored in more detail in this section.

Switching back and forth between two unrelated tasks in a dual task paradigm is thought to tax people's cognitive load (Lavie, 2010). In a set of experiments, Lavie and colleagues (2004) gave participants a dual task, in which they memorised a set of letters. Subsequently, participants performed a Flanker task and were then presented with a single letter and they had to indicate whether it was included in the initial string of letters that they memorised or not. Cognitive load was manipulated by varying the number of letters that had to be maintained. Importantly, across the experiments, the authors found that with increased cognitive load, participants showed greater interference on the Flanker task (e.g. slower reaction times). Thus, confirming that high *cognitive* load leads to *increased* distractor processing and therefore opposing effects as observed in perceptual load.

Similarly, the first experiment by Konstantinou and Lavie (2013; explained in more detail under visual working memory) indicated that with both perceptual and visual working memory load participants are less likely to process additional information in the periphery. In a second experiment Konstantinou and Lavie (2013) asked participants to memorise a string of digits before completing a dual change detection and visual search (based on experiment 1) and found that when increasing the cognitive load by asking participants to memorise a random string of digits, the sensitivity to detect an additional shape presented in the periphery of a visual search task is *increased*. Thus, in line with the predictions of the load theory, this suggests that reduced priority over information can be asserted under a high cognitive load and the additional shape in the periphery is processed.

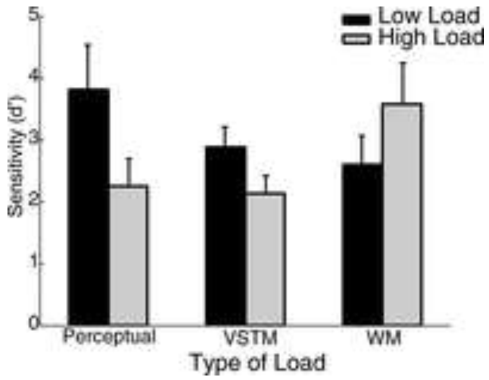

Figure 2. Figure extracted from (Konstantinou & Lavie, 2013), showing detection sensitivity of a stimulus in the periphery in a visual search task when manipulating perceptual load, visual maintenance, and cognitive load (abbreviated as VSTM and WM respectively in the figure) under high and low levels of load.

Similarly, Konstantinou and colleagues (2014) found that when comparing performance on tasks that require visual working memory (e.g., visual maintenance taxing perceptual load) with cognitive load tasks (taxing cognitive resources through active verbal rehearsal), that distractor processing on a Flanker task results in opposing effects for distractor interference. Whereas the tasks that loaded on visual working memory resulted in reduced interference under high levels of load, the cognitive load task showed increased interference under high levels of load, providing further evidence for the predictions of the Load Theory.

Other studies also show that the cognitive load manipulation across modalities is successful when combining auditory and visual components (Brand-D'Abrescia & Lavie, 2008). In a set of experiments Brand-D'Abrescia & Lavie (2008) replicated the findings of reduced distractor interference in conditions that required cross-modal involvement and importantly in one experiment (experiment 3) by combining two perceptual tasks. This will be relevant for Chapter 2 and discussed in more detail.

Whilst the cognitive control mechanism can be likened to other mechanisms proposed in the literature, such as the central executive in the working memory model (A Baddeley, 1992, previously highlighted under visual working memory), no direct predictions about distractor processing are made in other theories. However, the cognitive mechanisms are thought to be related to previous executive function mechanisms with their core in the pre-frontal network areas. For instance, de Fockert & Theeuwes (2012) used dual verbal rehearsal letter and visual search task while participants were scanned in an fMRI machine. They found that increased attention capture of irrelevant information is associated with greater pre-frontal cortex activation under high cognitive load. Load Theory proposed that during such tasks, executive cognitive load taxes prefrontal activity involved in resolving and suppressing processed distractor information, unlike additional sensory recruitment areas that are required for perceptual load paradigms (e.g. as discussed Konstantinou et al., 2014).

Cognitive Load in Autism.

Executive cognitive load is thought to require cognitive pre-frontal cortex activation to be successfully executed. Whilst some literature introduced throughout the present chapter points towards pre-frontal cortex dysfunctions in autism (Hughes et al., 1994), the cognitive profiles in autism appear to be heterogeneous (White, 2013). Not much is known about manipulating cognitive load in line with Load Theory using dual tasks in autism. García-Villamisar and Sala (2002) administered a single and dual task that involved tracking objects and digit recall separately or simultaneously. In the study, autistic adults showed difficulties maintaining the task performance for the dual task condition compared to non-autistic adults. This could be suggestive of increased distractor processing under high cognitive load. The use of standardised executive function tasks such as n-back tasks that heavily load on cognitive control, suggests that autistic people show difficulties completing those tasks. However, those tasks do not allow investigation of the role of distractor processing. Given the increased perceptual capacity in autism, the question remains as to whether the results extend to cognitive load. In the second Chapter of this thesis I will address this question using a Load Theory paradigm to assess cognitive load in autism.

Other Influences on Attention.

Altered attentional process have been also found in conditions such as anxiety (Berggren et al., 2015), depression (e.g. Owens et al., 2012) and ADHD (Luo et al., 2019). Given the high overlap with each of these conditions in autism (as outlined in this chapter, see co-occurring conditions), the role of anxiety, depression and ADHD on attention in autism should be explored further. For instance, a recent study using causal modelling suggests that ADHD and autism show (amongst other clusters) pathways for a common underlying aspects of inattention (Sokolova et al., 2017). Moreover, our own work has also demonstrated an association between self-reported sensory sensitivity (e.g. hypersensitivity) and perceptual load in autistic and non-autistic adults (Brinkert & Remington, 2020). Therefore, throughout this thesis I will use self-report questionnaires to assess underlying co-occurring ADHD, mental health and sensory sensitivities associated with autism to explore the role of attention in autism further.

Likewise, it is important to note that in the autism literature a large body of work focusses specifically on social aspects of attention. Social attention research is for instance concerned with joint attention or face processing (Salley & Colombo, 2016). Face processing as shown by Lavie and colleagues (2003) is a special case to attention, suggesting that faces are processed in an automatic and mandatory fashion, regardless of load and at the expense of the central task. In autism research however face processing does not follow the same salience (e.g. see Sasson, 2006). Studies show that face-processing in autism using eye tracking and pupil diameter measures as an index for arousal shows consistent differences in attention capture (Nuske et al., 2016). Therefore, it would be beyond the scope of this thesis to explore these special cases of attention as this thesis focuses on the basic attentional processes in autism. The literature reviewed throughout this chapter and across the thesis will focus only on non-social attention. However, more on social aspects of attention in autism can be found here (Guillon et al., 2014; Mundy, 2018).

Aims of this Thesis.

The literature discussed above detailed the differences in aspects of attention in autism. Throughout this Chapter, I identified gaps in the literature that have not been addressed in the autism literature on selective attention abilities under influences of 1) cognitive load and 2) visual working memory load.

More specifically, in Chapter 2, I will explore cognitive load in autism using a dual visual discrimination- Flanker task and will assess congruency effects under cognitive load, using a paradigm that has been used in the context of Load Theory.

In chapter 3, I will specifically investigate the role of visual maintenance and distractor interference using a change detection task. To achieve this, I will measure concomitant ERP markers of CDA as a marker for visual working memory and filtering efficiency. This will help elucidate whether visual working memory capacity is enhanced in autism in line with the previous findings of enhanced perceptual capacity in autism.

Chapter 4 will build directly on Chapter 3 by contrasting visual working memory and perceptual capacity directly using two qualitatively similar paradigms measuring CDA and N2pc.

Chapter 5 concerns practical steps that could be taken to ameliorate difficulties experienced by autistic adults as a result of altered attentional behaviours. There is evidence that selective attention can be trained through cognitive training paradigms and meditation. In my final study, I will assess the feasibility of a neurofeedback mindfulness intervention for autistic adults.

Chapter 2

Assessing Cognitive Control Capacity in Autistic and Non-autistic Adults in an Online Study

As outlined in Chapter 1, Load Theory makes distinct predictions regarding how distractors are processed under perceptual (passive) versus cognitive (active) load. Under high *perceptual* load distractor processing is decreased (Lavie, 2010), reflecting the exhaustion of perceptual capacity. Conversely, Load Theory proposes that under high *cognitive* load (when a task challenges executive function resources, e.g. through active maintenance or shifting of information) distractor processing is increased as no available resources to prioritise targets and block out distractors is diminished.

So far passive processes have been analysed in the autism literature using the framework of Load Theory. In previous autism research Remington et al. (2012) found that autistic people show an increased perceptual capacity, (i.e., processing more information simultaneously). As outlined in more detail in Chapter 1, this enhanced perceptual capacity also indicates that more task irrelevant information can be processed if a task does not fill the perceptual capacity. Active processes may also play a role in distractor processing in autism. Importantly, it has not been explored whether this increased perceptual capacity in autism is accompanied by an equivalent enhancement in cognitive control to help manage the additional information being processed. Therefore, the present Chapter will investigate selective attention under cognitive load.

According to the Load Theory, when a task requires high cognitive load, it taxes multiple demands (Lavie, 2010). In a classic dual task, participants memorise a digit string sequential and perform a visual search task (Lavie et al., 2004). When memorising a digit span, the ability to prioritise targets and block out distractors is diminished, and participants process more distractors compared to trials where participants compete a simple visual search task.

Although, similar effects (i.e., increased distractor processing) were found when combining two perceptual tasks in a dual task paradigm, switching between two tasks also places demands on the cognitive control function (Brand-D’Abrescia & Lavie, 2008). Thus, distractor processing is increased and interference with the goal relevant information in the dual task condition suggests a taxation of cognitive resources instead of reducing distractibility as it would if perceptual resources were taxed.

To successfully complete a dual task paradigm in the framework of the Load Theory task switching abilities and inhibition is required. As discussed in Chapter 1 the majority of research in the cognitive control literature has employed neuropsychological tasks such as the Wisconsin Card Sorting task (Grant & Berg, 1948), CANTAB shift task (Cambridge Cognition, 2002). These tasks give an overall measure on performance in cognitive control. However, these paradigms do not measure attention or processing of task irrelevant information within the task. Meta-analyses have been used to synthesise research on overall executive function in autistic and non-autistic people. In a recent meta-analysis Demetriou and colleagues (2017) suggest that set shifting abilities mature with age, whereas autistic children present more difficulties with cognitive flexibility compared to adults, however, effect sizes were moderate for adults (hedges g=.48). This indicates that the difficulties are still observed in adulthood. A review that focused on cognitive flexibility tasks by Leung and Zakzanis (2014) suggests that on average autistic participants showed more cognitive flexibility difficulties than non-autistic participants. However, whilst some studies included in the meta-analysis produced large effect sizes, these effects were not universally found. An issue with previous assessments of cognitive control is that a range of different methodological assessments are used. These inconsistencies might also be related to terminology that is used interchangeably with general executive functions in the autism literature. To add to the problematic of cognitive control tasks in the autism literature, Geurts et al. (2009) noted that cognitive flexibility does not map onto assessments of behavioural flexibility in autism and therefore lacks ecological validity.

Whilst there is some indirect evidence for reduced cognitive control and cognitive flexibility within the set shifting literature in autism, it remains unclear how selective attention contributes to these processes and how cognitive control capacity fits with the framework of the Load Theory in autism. Yet, this issue has not been addressed in autism and is a fundamentally important question, given the increased distractor processing that can result from enhanced perceptual capacity. Understanding the active cognitive control processes, and how they may relate to this greater perceptual capacity, is important if we are to effectively support autistic individuals when they experience the more challenging aspects of increased capacity.

Here, I examined selective attention under cognitive control load by employing an experiment similar to Brand-D’Abrescia and Lavie's (2008, experiment 3). More specifically, autistic and non-autistic adults’ task coordination abilities are tested on a visual discrimination and a Flanker task (Eriksen & Eriksen, 1974). In a standalone letter Flanker task with either congruent or incongruent letters, response competition effects were assessed for reaction time and accuracy. The cognitive control load was manipulated by adding a dual task condition in which participants completed the visual discrimination task and Flanker task sequentially to assess task coordination abilities and distractor processing under cognitive load. In the visual discrimination task participants are asked to identify visual features of a target letter from within an array of target letters and report the orientation of the target (upright or inverted). The performance is then contrasted with trials in which participants complete a standalone Flanker task.

It was predicted, in line with the Load Theory and findings from Brand-D’Abrescia and Lavie's (2008) study, that combining two perceptual tasks in a visual discrimination task paradigm would result in greater interference by irrelevant distractor information (incongruent letters) on the Flanker task; compared to completion of the Flanker task alone. Both tasks are of perceptual nature, the coordination during the multiple component condition[3] requires task shifting abilities and is therefore thought to load executive function abilities. Congruency effects, the difference scores between congruency conditions (subtracting the mean reaction time and accuracy of congruent trials from incongruent trials), will be used to assess differences in reaction time costs. A high score indicates less efficient interference control. If autistic participants show increased reaction time congruency effects (costs under incongruent - congruent trials) for reaction time and accuracy under the multiple task condition (high load) condition, this would indicate an increased interference by irrelevant information and therefore a decreased cognitive capacity. However, if autistic people's cognitive capacity is increased similar to the perceptual capacity, this would result in decreased reaction time congruency effects for the task irrelevant information. This may be accompanied by reduced error rates under multiple task conditions as the available cognitive control capacity is not exceeded.

Methods

Participants

Autistic and non-autistic adults took part in the present study. A priori power analysis (Faul et al., 2009) was conducted for the between subjects effects ($\alpha = 0.05$, $1-\beta = 0.95$) to assess the required sample size for the study. As the data was collected online, a medium effect size (f=.4) was used to determine the sample size. The minimum required sample size was 59. As noise is likely in online experiments and additional autism diagnostic criteria were applied the required sample size was set to 100 to allow for data to be excluded. Participants were recruited through Prolific (www.prolific.co), a participant crowdsourcing platform for online experiments. Participants were pre-screened in Prolific based on:

1) Age; age range 18-40 years,

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[3] Note that the Brand-D'Abrescia and Lavie (2008) refer to the original paradigm as dual and single task conditions, I will be using the term multiple component and single task condition to avoid mis-characterisation that the tasks was completed concurrently.

2) Geographical location (currently residing in the UK),

3) English as their first language to ensure that the participants were able to complete the online questionnaires and understand the task instructions

4) Access to a desktop computer with internet connection

Half of the participants were recruited based on an autism diagnosis that they provided in the demographic background information on Prolific.

A total of 108 participants completed the study (n= 53 reported a clinical autism diagnosis, n=54 reported no diagnosis of autism and n=1 self-identified as autistic). Participants who performed below chance level accuracy were removed as it is likely that performance below chance reflects a lack of task engagement or misunderstanding of task instructions. Thus, a total of 27 participants (16 in the autism group and 11 in the non-autistic sample) were excluded from the study to ensure a sufficient task engagement and accuracy rates. An additional 4 participants (n=3 autistic; n=1 non-autistic) were excluded from the sample due to unavailable trials for correct reaction time data on the multiple component task condition. The social responsiveness scale (SRS, Constantino & Gruber, 2012, see procedure section for more detail) was assessed as an autism trait measure to ensure that participants meet the clinical threshold of autism of 60 in the autism group and that score below the clinical threshold in the non-autistic sample. In the non-autistic sample, 13 participants were excluded as they scored above the clinical threshold for autism. Five participants in the autistic sample did not meet the threshold for the SRS and an additional participant in the autism group was removed as they reported that they self-identified as autistic, did not have a clinical autism diagnosis and did not meet the SRS cut off for autism. Therefore, the total sample consisted of 58 participants (n=29 in each group, see Table 1 for more details on demographic information).

Table 1. Demographic information for the participants included in the study

		Autistic (*n* =29)		Non-autistic (*n* =29)			
		M	(SD)	M	(SD)		
		Range		Range		*p*-value	
Demographics							
	Gender (F:M:NB)[a]	15:12:2		19:10:0		.23	
	Age (in years)	25.21	(6.28)	27.10	(5.51)	.27	
		18 – 50		19 - 55			
	Handedness L:R:A[b]	23:5:1		25:4:0		.37	
	Employment (n/%)						
	Fulltime	12	(41.4)	12	(41.4)		
	Part-time	5	(17.25)	8	(27.6)		
	Unpaid work[c]	3	(10.35)	2	(6.9)		
	Unemployed	2	(6.9)	4	(13.8)		
	Other	4	(13.8)	2	(6.9)		
	Missing	3	(10.35)	1	(3.45)		
	SRS-2	75.17	(6.97)	47.10	(12.95)	.001	***
		60 – 90		0 - 59			
	DASS-21	34.28	(13.77)	15.90	(8.94)	<.001	***
		9 – 60		0 – 30			
	DASS- Anxiety	20.34	(9.26)	6.21	(4.55)	<.001	***
		6 – 40		0 - 14			
	DASS-Depression	22.62	(10.39)	11.79	(8.15)	<.001	***
		4 – 42		0 - 30			
	DASS – Stress	69.03	(28.04)	31.10	(17.47)	<.001	***
		18– 120		0 - 58			
	ASRS	12.66	(4.41)	11.52	(4.51)	.34	
Co-occurring conditions (frequencies; n/(%))							
	ADHD	3	(10.34)	7	24.14		
	Dyspraxia	2	6.90	1	3.45		
	Dyslexia	4	13.79	3	10.34		
	Learning Disorder	1	3.45	2	6.90		
	Prefer not to say	0	0	1	3.45		

Note. [a]Gender F: M:B; F= Female (including transgender female), M= Male (including transgender male), NB= Non-binary; [b]Handedness L:R:A; L=Left handed, R= Right-handed, A= Ambidextrous, [c]Employment; unpaid work (including disability or retirement), SRS-2: Social Responsiveness Scale, second edition (Constantino & Gruber, 2012), DASS-21 (Depression Anxiety, Stress Scales -21,Brown et al., 1997); ASRS (Adult ADHD self-report screener; Ustun et al., 2017).

Procedure

The study was approved through the postgraduate ethics approval procedure of the UCL Institute of Education. All participants completed the information sheet and consent form before they started the online study. The experimental software platform Gorilla (Anwyl-Irvine et al., 2020) was used to administer the questionnaires and experimental task. The study took around 20 minutes to complete and participants received £2.50 for their time.

Measures

Self-report measures

Participants completed four self-report questionnaires on the experimental software platform Gorilla (Anwyl-Irvine et al., 2020):

1. ***Demographic Information.*** Participants provided demographic information that included their age, gender, handedness, and diagnostic information.

2. ***Social Responsiveness Scale***, second edition (SRS-2; Constantino & Gruber, 2012), a validated and reliable 65-item scale used to assess self-reported autism traits. On a 4-point Likert scale (0=not true to 3=almost always true), the categories of restricted interests and repetitive behaviour and social aspects of awareness, cognition and communications were assessed. The scale has excellent test-retest reliability (.88-.95) and an interrater reliability of (.61-.92) and good internal consistency (α=.95; Bruni, 2014).

3. Adult ADHD self-report screener. Participants also completed an Adult ADHD self-report screener (ASRS-V1.1, (Ustun et al., 2017) which is a validated clinical diagnostic tool that consists of 6 items to reliably assess ADHD symptoms in line with the DSM-5 ADHD diagnostic criteria. Participants respond on 5-point scale, (0 = Never, 1 = Rarely, 2 = Sometimes, 3 = Often, and 4 = Very Often) to questions such as *How often do you have problems remembering appointments or obligations*?. A high score on the scale indicates higher levels of ADHD traits. The scale measures inattentiveness on four items and hyperactivity and impulsivity on two items. The sensitivity of positively predicting ADHD is at .94 and for a negative prediction at 23.5 (Kessler et al., 2007). Internal consistency of items was high (Spearman's rho ranged between .61-.79) and Cronbach's alpha was fair at .54 for the total scale, .57 for the inattentiveness scale and .59 for the hyperactivity and impulsivity scale (Silverstein et al., 2018). The overall scale was test-re-test reliability of .78.

4. Depression and Anxiety Stress Scales. The Depression and Anxiety Stress Scales (DASS-21; Lovibond & Lovibond, 1995) was used as it is thought to reliably assess depression (α=.96), anxiety (α=.84) and stress (α=.93; Brown et al., 1997). The scales assess the acute symptoms "over the past week" with 7 items per subscale. Participants made responses on the 0-3 scale (0= Did not apply to me at all; 1= Applied to me to some degree, or some of the time; 2= Applied to me to a considerable degree or a good part of time; 3 = Applied to me very much or most of the time). Scores were multiplied by two, a score on the stress scale below 10 was classes as normal, on the anxiety and depression scale a score of 6 and 9 respectively were classed as below clinical levels. The scores were multiplied by 2, in line with the scoring manual of the DASS-21.

Experimental Task

Online Working Memory Flanker Task. The experiment was similar to Brand-D'Abrescia and Lavie's (2008, experiment 3) visual processing task. The task consists of single (a) and multiple component (b) sequences (see Figure 3 for more details).

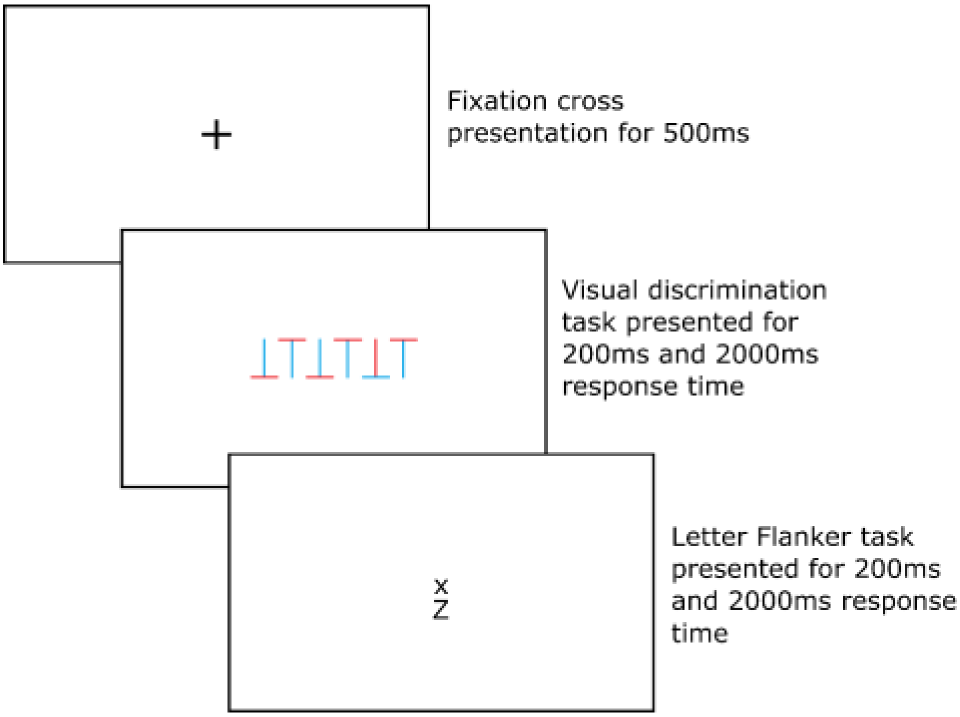
a) The single task consisted of a letter Flanker task. At the beginning of each trial, a fixation cross was presented in the centre of the screen (for 500ms), followed by two letters. The target letter (x or z) was presented in the centre of the screen. The target letter was presented in lower cases alongside a second capitalised distractor letter. The distractor letter was either presented below or above the target letter. On half of the trials the distractor letter was congruent with the target letter and on the other half of the trials incongruent (e.g. the target letter was an x the distractor letter was a Z). The two letters were presented for 200 ms and participants were asked to report whether the target letter was an x or a z as quickly and accurately as possible within a 2000ms time window by pressing the "K" or "L" key on the keyboard. Participants completed eight practice trials for the Flanker task, the instructions on which keys were to press remained on the screen throughout the practice block.

b) In the multiple component task sequence, each trial began with fixation cross (that remained on the screen for 500ms) followed by a visual discrimination task and then the letter Flanker task. In the visual discrimination task, six inverted or upright T's were presented lined up next to each other in the centre of the screen. The letter Ts were made up of one red and one blue line. The target letter had a vertical red line and a horizontal blue line. All other letters were presented in the opposite colour combination (vertical blue line and horizontal red line). The target letter was presented in either of the four central letter positions of the 6 letter sequence. The letters were presented for 200ms and participants had 2000ms to indicate whether the target letter was oriented upright or inverted by pressing the "A" or "S" key on the keyboard using two adjacent fingers (of the left hand) on the keyboard. After participants logged their response on the keyboard or after 2000ms the letter Flanker trial appeared in the centre of the screen as described in the single task condition and participants were asked to respond to the target letter as quickly as possible. Participants had 2000ms to log their response by pressing the “K” or “L” key on the keyboard before the next trial started.

Detailed written instruction supported by visual images were presented to the participants before they started the practice trials. The instructions remained on the screen while participants completed the practice blocks. Participants completed practice trials for the single and multiple component sequences first (16 trials each), before they started with the main experiment. For the main experiment, one block of single tasks followed by one block of multiple component task sequences (64 trials each) were completed. Participants received feedback on their performance throughout the task by presenting a green tick icon for correct answers and a red cross for incorrect responses. The stimuli were presented on a white background.

The stimuli used in the paradigm were based on Brand-D’Abrescia and Lavie's, (2008) paradigm. Controlling for the screen resolution, screen size and browser size was not possible due to the remote nature of the study, therefore it is not possible to determine the visual angle of the objects.

Figure 3. Sample trial order for the experimental task. The trial illustrates a multiple component sequence with the visual discrimination task (the target letter with the red vertical and blue horizontal line in the fourth position of the sequence is inverted) and a letter Flanker (incongruent trial).



Note. Depiction of the multiple component trial, with the visual discrimination task requiring to identify the blue horizontal line of the T is inverted. Subsequently a letter flanker trial is presented with the smaller target in the centre of the screen an additional letter (incongruent) presented below. In the single task condition, the fixation cross and the letter Flanker were presented only. Depiction of trial is not to scale.

Data Analyses

Mean reaction time (the mean latency (ms) of responding after Flanker stimulus onset) for correct responses on the Flanker task, and mean accuracy on the Flanker probe display were calculated for the multiple component (high load) and single (low load) task condition each with incongruent and congruent trials. The data were entered into a 2 (congruency: congruent vs incongruent) x 2 (Load: single vs multiple component) x 2 (group: autistic vs non-autistic) mixed analysis of Variance (ANOVA). In addition, congruency effects were calculated as the difference between mean reactions times of congruent trials that were subtracted from incongruent trials. The mean accuracy and mean reaction time for correct responses were also calculated for the visual discrimination task and entered into independent sample t-tests. Additional exploratory Pearson's correlation coefficient was used to explore the relationship between the self-report measures of mental health and ADHD and the congruency effects in the multiple component condition. Bonferroni corrections for multiple comparisons were applied.

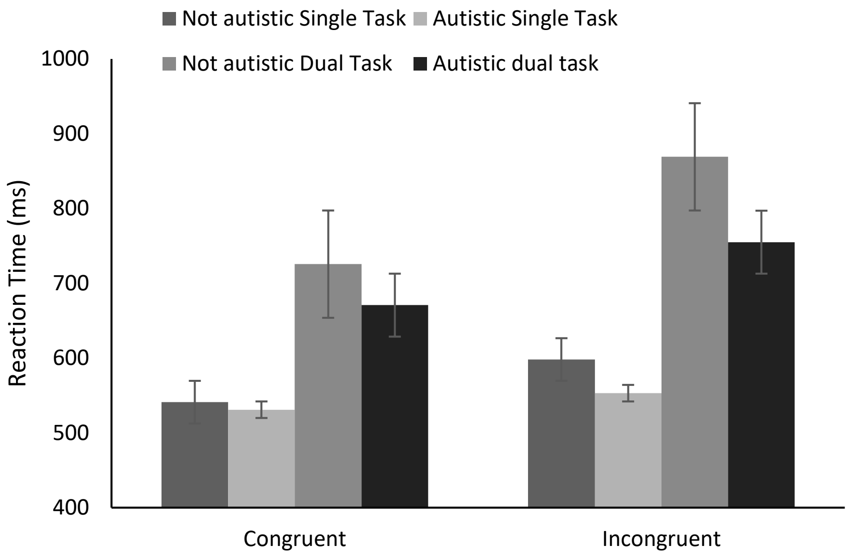
Results

Flanker Task

Reaction Times

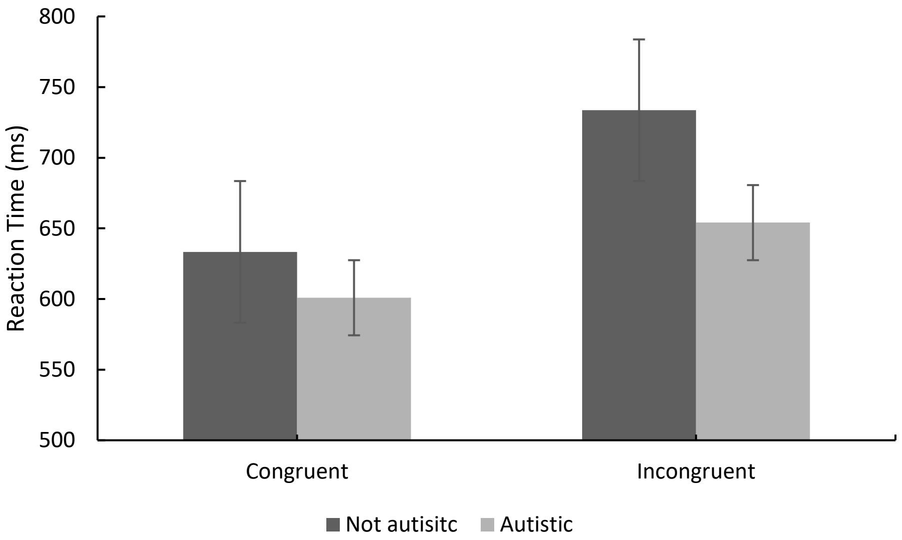
The study revealed a main effect of load (F(1,56)=103.45, p<.001, η^2=.24, see Figure 4) and a main effect of congruency (F(1,56)=67.91 p<.001, η^2=.04) on reaction time. The reaction times were increased during the multiple component task (high load) condition compared to the single task (low load) condition. Similarly, as expected the reaction times were also increased during incongruent trials compared to congruent trials. This suggests that the load manipulation was successful. The interaction between congruency and load was significant (*F*(1,56)=21.26, *p*<.001, η^2=.01), indicating that distractor compatibility congruency effect was increased for multiple component tasks compared to single task conditions. There was no significant 3-way interaction (*F*<1), indicating that the relationship between task load (multiple component or single tasks) and congruency (congruent or incongruent trials on the Flanker task) was not significantly different for the autistic and non-autistic participants. There was also no main effect of group (*F*(1,56)=2.43, *p*=.12) suggesting that overall reaction times were not different across the groups, (i.e. one group faster at responding than the other). Importantly, the interaction between congruency and group was significant (F(1,56)=25.56, *p*<.001, η^2=.01) suggesting that congruency affects the two group differently. Inspection of suggests that autistic people were faster in the incongruent condition compared to the non-autistic sample. Although, the independent sample t-test indicate that reaction time for the groups was insignificant for the two groups for incongruent trials (*t*(56)=1.86, *p*=.07, *d*=.49), there were some inclinations towards slower responses in the non-autism group (*M*=654.04, *SD*=148.67) compared to the non-autistic sample (*M*=733.6, *SD*=175.65). Congruent trials did not differ (*t*(56)=1.17, *p*=.29. *d*=.23) between the autistic sample (*M*= 600.88, *SD*=118.59) and the non-autistic sample (*M*=633.34, *SD*=113, see Figure 5).

Figure 4. Mean reaction time (ms) by conditions and group



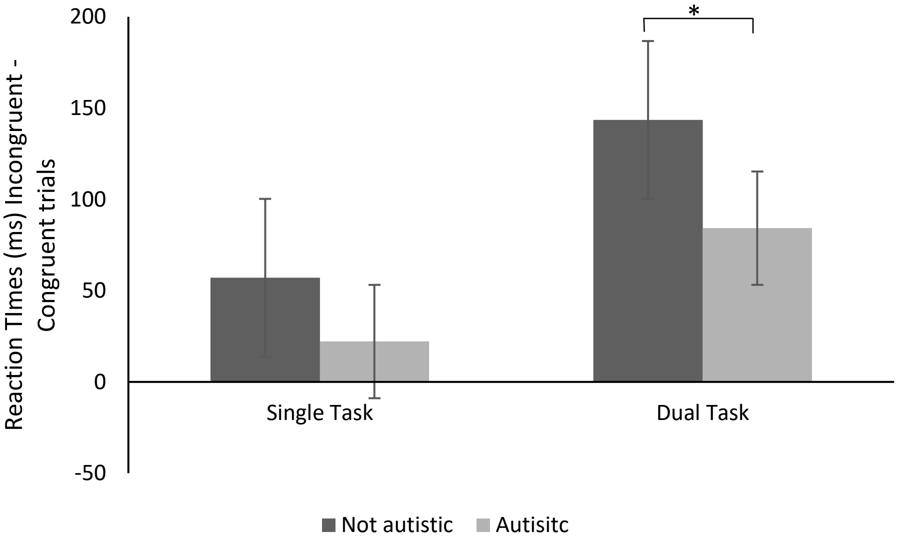
Note. Mean reaction times are presented as a function of task condition and congruency

Figure 5. Reaction times as a function of congruency and group



As expected, in line with the Load Theory, distractor compatibility effects (mean reaction times for incongruent trials – reaction time for congruent trials) were larger in the multiple component task condition compared to the single task condition, suggesting that the load manipulation was successful (see Figure 6). Independent sample t-tests were carried out to test the congruency compatibility effects across the groups. On average, the autistic participants (*M*=84.21, SD=65.97) were significantly (*t*(56)=2.63, *p*=.01, d= .55) quicker compared to non-autistic participants (*M*=143.49, *SD*=152.24) during multiple component tasks. The autistic participants showed decreased distractor compatibility effects on the Flanker task when the Flanker task was combined with the visual discrimination task. The reaction time congruency effects in the single task condition did not significantly differ between the groups (*t*(56)=1.92, *p*=.06, *d*=.27; Autistic sample: *M*=22.12, *SD*=37.04; Non-autistic sample: *M*=57.04, *SD*=61.02).

Figure 6. Reaction time congruency effects as a function of Load by Group



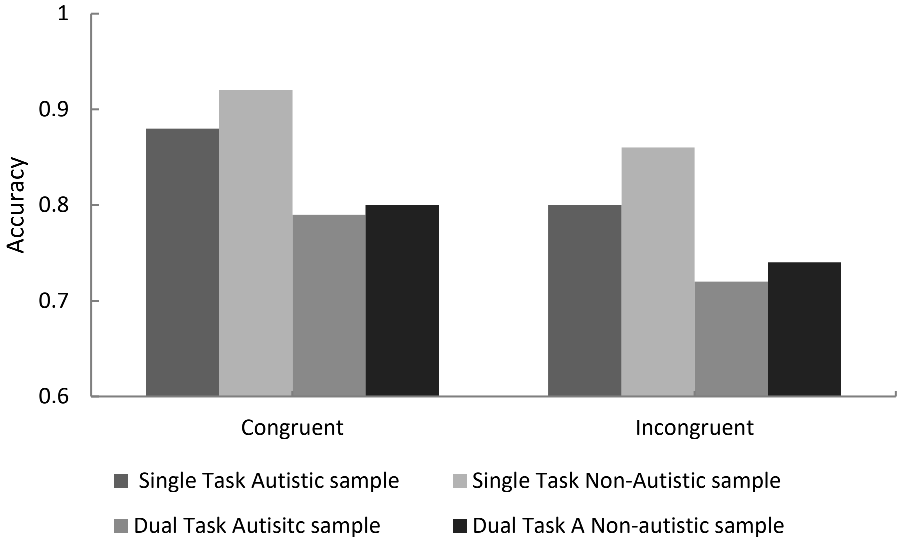
Note. Mean Reaction Time presented in milliseconds, the reaction time congruency effects were calculated by subtracting the mean reaction time for congruent trials from congruent trials. The difference for the multiple component task is significant (p=.01).

Accuracy

The accuracy data for the Flanker task, revealed a main effect of load (*F*(1,56)=38.58, *p*<.001, η^2=.10) and a main effect of distractor compatibility (*F*(1,56)=51.01, *p*<.001, η^2=.04).

Accuracy was significantly higher under for the single task condition (compared to the multiple component task condition) and during congruent trials (compared to incongruent trials) in the task (see Figure 7). There was however neither a main effect of group (*F*(1,56)=1.02, *p*=.32, η^2=.01) nor a 3 way interaction between group, congruency and task condition on accuracy or between group and congruency and group and task condition (*F*s<1).

Figure 7. Bar graph for accuracy as a function of congruency by group and task condition



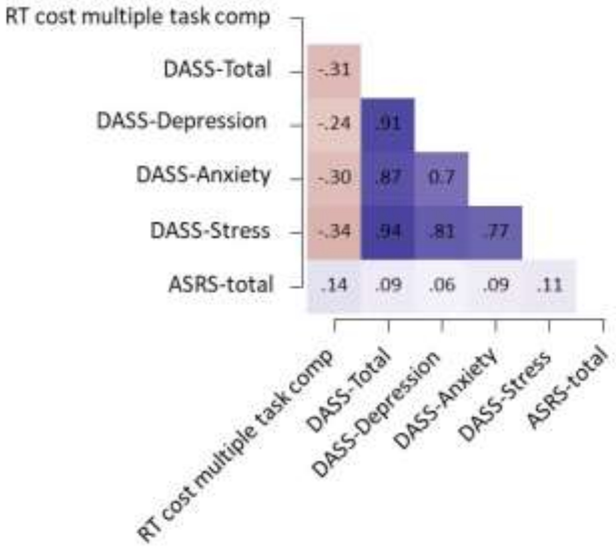
Visual Discrimination Task

To access whether there were group differences on performance on the visual discrimination task, independent sample t-tests were conducted for reaction time and accuracy. The reaction time difference was not significant (*t*(56)=1.88, *p*=.07, d=-.49). Although the effects were not significant, the patterns of reaction times are similar to the reaction times of the Flanker task showing inclinations for speeded responses in the autistic group (*M*=817.89, *SD*= 222.17) compared to the non-autistic sample (*M*=929.38, *SD*=229.98). There was no significant difference in accuracy (*t*(56)=1.25, *p*=.22, *d*=.33) on the visual discrimination task between the autistic sample (*M*=.79, *SD*=.17) and the non-autistic sample (*M*=.74, *SD*= .15).

Additional Exploratory Analysis

To examine possible confounding factors that may have influenced task performance in particular the differences for congruency effects on the multiple component task condition, correlations were run for congruency effects of the high load condition, the total DASS-21 score, the three subscales of the DASS-21, and the ASRS. Bonferroni corrected ($\alpha_{adjusted}$= .008) Spearman's correlations revealed, as expected, that the DASS-21 total score and the subscales were positively inter-correlated (*p*s<.001), suggesting that a higher score on the total or subscale is linked to a high score on the subscales. The congruency effect (cost between incongruent and congruent trials) with the DASS-stress scale, as well as anxiety and the total DASS-21 scale did not survive Bonferroni corrections. ADHD symptomatology (as measured on the ASRS) was not significantly associated with the self-reported mental health scores or the reaction congruency effects Figure 8.

Figure 8. Spearman's roh heatmap for the correlations between reaction time congruency effects for the multiple component task condition and the ASRS, DASS-21 and the subscales
Spearman's rho heatmap



Note. The reaction time congruency effects were calculated by subtracting incongruent from congruent trials for the multiple component trials. DASS-21 (Depression Anxiety, Stress Scales -21, (Lovibond & Lovibond, 1995) and the subscales for depression, anxiety and stress; ASRS (Adult ADHD self-report screener Ustun et al., 2017)

Discussion

The aim of the present study was to investigate whether cognitive control capacity, analogous to the increased perceptual capacity, is increased in autism. Importantly, the results reveal that autistic people were less distracted by incongruent information compared to the non-autistic sample. There are two possible interpretations for the results. Firstly, the result could be interpreted using the framework of the Load Theory. Load Theory suggests when increasing cognitive load (for instance by coordinating the demands of two perceptual tasks) this increases distractor interference effects (e.g. increased processing of incongruent information on the Flanker task) as there is no available cognitive control capacity to prioritise targets and ignore task irrelevant information. Importantly, in the present study, the way in which varying concurrent demands in cognitive load impacted selective attention abilities suggests reduced distractor processing in the multiple component task in the autistic sample compared to the non-autistic sample. Overall, the results indicate that the load manipulation was successful and reaction time increased with increased cognitive load in the non-autistic sample. Interestingly, the mean reaction time congruency effects were significantly decreased for the autistic compared to non-autistic adults in the multiple component task condition. This suggests that autistic people displayed *decreased* levels of distraction (better ability to priorities targets) under the multiple component task condition (when cognitive control demands are high) and indicates preliminary evidence for an *increased cognitive capacity*. Although not significant, reaction times indicated inclinations for speeded responses in the autism group for congruent trials in single task conditions (p=.06), incongruent Flanker trials and visual discrimination (both *p*s=.07). Importantly, the speeded responses did not come at cost of accuracy, there were no group differences accuracy on the visual discrimination or Flanker task. However, the reduced distraction from task incongruent information was seen, suggesting that autistic people had cognitive capacity available to ignore the distractor and prioritise the task-relevant information. This could therefore be seen as preliminary evidence for an increased cognitive capacity. The results extend on previous findings of an enhanced perceptual capacity and suggest that both perceptual and cognitive capacity might be enhanced in some situations in autism.

It has to be noted that it is currently unclear that how an increased cognitive capacity would manifest across levels of load, as it has not previously been analysed in the framework of the Load Theory. Therefore a second alternative might be that autistic people simply show reduced distractibility by the incongruent information, as the results did not yield a significant 3-way interaction. The autistic participants showed a reduction in the low load and high load condition, however the incline was proportionate to the non-autistic sample. Therefore, the results might be interpreted as an overall reduced distractibility in autism.

Importantly, the present study has – yet again - yielded evidence for an advantage in autism, however, the question is how do the findings fit with the previous literature? As previously indicated (in the introduction of this chapter and Chapter 1) there is mixed evidence on inhibition abilities. As such variants of Flanker tasks, have indicated decreased performance in autistic children (Adams & Jarrold, 2012; Christ et al., 2007, 2011), however other studies with adolescents yielded no group differences (Boland et al., 2019; Van Eylen et al., 2015). Aspects of inhibition are largely unexplored in adulthood on Flanker tasks in autism, whilst Dichter & Belger (2007, 2008) found no behavioural differences in using a modified Flanker version with faces stimuli. South et al. (2010) used a standard Flanker task and reported no differences for reaction times but indicated increased error rates in the autism sample. With such limited studies available in adulthood, it is currently unclear whether cognitive inhibition is altered in adulthood.

The differences between my findings and those showing the opposite pattern may be due to methodological discrepancies between the various tasks employed. As alluded to previously, a number of different Flanker task variations are available. The most commonly used Flanker task consists of letters or arrows where the target detection is manipulated by placing distractors (typically four) horizontally on each side of the target that is presented in the centre of the screen. However, in the present study, the presentation of the distractor was in vertical vicinity of the target. Interestingly, leading to opposing findings compared to the previous literature. Importantly, the paradigm in the present study was similar to Brand-D'Abrescia and Lavie (2008) in which the load manipulation was further increased by presenting the distractor in a capital letter next to the central target letter. Therefore, this could have led to an advantage based on a local processing bias as previously discussed in the Weak Central Coherence theory (Happé & Frith, 2006a).

The findings from the present study highlights that the presentation format of information could have important real life implications and underestimated abilities of autistic people in the previously literature. This could have a potential impact on work places and education settings in which the cognitive demands of two perceptual tasks simultaneously may be help autistic people to more efficiently process task relevant information, similar to recommendations made for in the perceptual load literature (A. Remington et al., 2019a). As such, it might be that concentrating on attending lecture slides, autistic people might be better at inhibiting other distractors that simultaneously happen in the environment. This could also closely align with anecdotal evidence of hyper focus, the ability to tune out distractors that has been frequently reported by autistic people (Russell et al., 2019). Importantly, the findings of the present study highlight future avenues of research of how attention abilities could be harnessed in the real world.

Importantly, previous studies have consistently indicated *increased* congruency effects and slower reaction times for participants with ADHD (e.g. McLoughlin et al., 2010; Uebel et al., 2010). Likewise, studies also reported slower reaction times for incongruent trials in depression (Dillon et al., 2015) and in anxiety larger markers for error related negative (discussed in Chapter 1). As there is a high prevalence for both ADHD and adverse mental health in autism (discussed in Chapter 1), in the present study co-occurring conditions including mental health and ADHD traits were assessed. However, correlations with reaction time congruency effects during the high load conditions did not survive Bonferroni corrections. Therefore, given the relatively small sample sizes it would be important to follow up the effects with larger sample sizes. Importantly though, the direction of the effects would be expected to result in opposing findings of the current study and might have also account for the heterogeneous findings presented in the previous cognitive inhibition literature, when co-occurring ADHD and aspects of mental health were not assessed (e.g. Boland et al., 2019; South et al., 2010).

Limitations

Whilst the present findings map an intriguing picture of improved cognitive control abilities in autism, there are however factors such as age and IQ that have been thought to moderate the group differences in some measures of inhibition but not on the Flanker task (Christ et al., 2007, 2011). In the present study, participants were matched on age, however no additional standardised measures were used to match participants on baseline cognitive abilities, such as general working memory capacity or measures of IQ, to avoid a lengthy study involvement and potentially risking performance detriments in the experimental task. Instead, as previously discussed, extra care was taken to assess additional co-occurring conditions that are thought to be linked to differences in inhibition and cognitive control to avoid confounding factors. However, the study should be replicated with matched cognitive abilities across the sample.

Likewise, in the present study the autism diagnosis was a self-reported diagnosis that was confirmed with the SRS-2, however, no additional assessment such as the ADOS-2 (Lord, Rutter, DiLavore, Riri, et al., 2012) could be conducted. In addition, due to the ongoing COVID-19 pandemic, the study had to be moved online instead of face-to-face in a controlled laboratory environment. Whilst the remote nature of the study enabled participants to take part across the UK who might not have normally been able to participate in research, there are limitations to the uncontrolled environment of the baseline and follow-up data completion.

For instance the visual angle of the presented object and data resolution cannot be standardised across participants. Therefore, a replication post-pandemic with a more controlled environment and additional diagnostic assessments for autism.

More generally, the study only manipulated cognitive load at high and low load. In line with the load theory predictions, the findings suggest that the asymptote in the autism group was not reached. Therefore, cognitive load could be manipulated by varying the amount of distractor letters in the visual discrimination task further to explore behavioural performance on a continuum.

In the present study, behavioural performance was assessed on a task that manipulated cognitive load by combining two perceptual tasks. The neural mechanism on how the tasks load on cognitive load remains however unclear. As discussed in the Chapter 1, sensory areas in the cortex play an important role in visual spatial attention and visual maintenance. As yet, the capacity limits of perceptual load have largely been unexplored using ERP markers of attention and maintenance in autism. Thus, in the next two chapters I will explore visual working memory capacity and perceptual capacity further using electrophysiological and behavioural markers.

Chapter 3
Working Memory Capacity and Filtering Efficiency in Autism

Chapter 1 outlined the evidence of altered selective attention in autism. Whilst autistic people perform well on some perceptual tasks, they tend to also show a heightened tendency to process task irrelevant information. The aim of the present chapter is twofold: some of the literature suggests filtering inefficiency in autism as a reason why autistic people may show differences in performance on visual attention tasks (J. W. Murphy et al., 2014b). In the present chapter, I investigated filtering efficiency by measuring EEG markers on a standard visual working memory task. Secondly, the overall visual working memory capacity was assessed to investigate that if visual working memory capacity in line with perceptual capacity is increased in autism.

As outlined in detail in chapter 1, our capacity to process information is limited, so that we have to selectively attend to task relevant and ignore task irrelevant information. One way to measure this is using a change detection task (Vogel et al., 2005). In a standard visual change detection task, participants are briefly presented with a visual array containing a varying number of objects (memory array). After a short delay a second screen containing a test array appears. The two arrays are identical on half of the trials, whereas on the other half of trials a change in the colour (or e.g. orientation/location, depending on the task) of one of the presented stimuli occurs. At the end of each trial, participants enter a forced-choice response whether they saw a change or not. The number of objects presented to the participant typically varies. The ratio of correct change detections to misses at the various array sizes allows visual working memory capacity limits to be established (e.g. Pashler, 1988). Previous studies suggest that one’s typical capacity limit is around four items that can be simultaneously held in visual working memory (Cowan, 2010). In addition to calculating behavioural markers for visual working memory capacity, electroencephalography (EEG) allows the assessment of neural markers within bilateral visual working memory tasks (Vogel et al., 2005; Vogel & Machizawa, 2004). Crucially, the EEG activation during the maintenance period in the posterior region becomes more negative and sustained, contralateral to processed stimuli, with increased set size. The negative posterior potential of the contralateral delay activity (CDA) reaches a maximum amplitude at around four items which is thought to represent a person's capacity limit and is highly correlated with behavioural markers of visual working memory capacity (Luck & Vogel, 2013). This method also allows us to assess whether additional task irrelevant information is processed. Filtering efficiency can be determined by contrasting the CDA on trials with solely task relevant information to trials with task irrelevant information (Vogel et al., 2005). Larger amplitudes suggest that more information has been stored, which suggests that irrelevant information is being maintained. When amplitudes in the distractor conditions are identical to those in conditions with the same amount of target information but no distractors, this suggests that no additional distractor information has been encoded (i.e. high filtering efficiency). In line with the CDA activation over occipital-parietal electrodes, the sensory recruitment hypothesis suggests that visual representations during visual change detection tasks are stored in the visual cortex (D'Esposito & Postle, 2015). In addition, the sensory recruitment hypothesis predicts that the same region is also involved in perceptual processing. It is crucial to note that the visual cortex activation is specific to maintenance of visual working memory and perceptual tasks (e.g. see D'Esposito & Postle, 2015 for a review), and that it is not active during executive function tasks such as N-back tasks (Cornette et al., 2001). This suggests that the visual system is fundamental for visual working memory and perceptual maintenance.

For the present study, I used a change detection task similar to that of Vogel and colleagues (2005) which focuses on the event-related Contralateral delay activity (CDA) component, thought to be sensitive to the number of items stored in the visual working memory (Vogel et al., 2005; Vogel & Machizawa, 2004). The task employed by Vogel and colleagues (2005) presented participants with varying numbers of target items (red rectangles) which they memorise for a short period of time before having to indicate whether a test array is the same or different from the original memory array. The negative posterior potential of the CDA showed a maximum amplitude at around 4 items which is thought to represent a person's capacity limit. Critically, on some trials of the change detection task irrelevant items (distractors, blue rectangles) were presented together with red target shapes. The authors directly compared the target and distractor conditions and showed that for people who efficiently filtered out irrelevant information, the CDA amplitude of response to a trial with two target items was equivalent to the amplitude of response to a trial with two targets and two distractor items (i.e. perfect filtering). Conversely, when people were less efficient at filtering, the CDA amplitude of response to a trial with four target items more closely resembled the amplitude of response to a trial with two targets and two distractor items (i.e. absolute equivalence would signify zero filtering). As such, the CDA offers a metric of filtering efficiency under varying levels of load (Vogel et al., 2005).

To examine visual working memory capacity in autism, the current study recorded EEG activation and concomitant CDA while participants performed a change detection task based on Vogel et al. (2005). To the best of my knowledge, this is the first time that there has been direct investigation of visual working memory capacity and filtering efficiency in autism, as indexed by the CDA, under different levels of visual working memory load. Specifically, I aimed to establish whether autistic individuals show an increased visual working memory capacity and filtering efficiency analogous to the perceptual capacity literature. A reduced visual working memory capacity would be reflected by a reduced CDA amplitude for the high cognitive load condition in the current task. In addition, comparing the CDA amplitude for the low load (two target items) vs. the distractor conditions (two targets plus two distractor items) will give an index of filtering efficiency. For example, those who can more effectively filter out non-target information will view both these conditions as equivalent (i.e. the same of targets exist in both) and not show a large discrepancy between CDA amplitude in the low load vs. the distractor condition. The difference in CDA amplitude between the low load and distractor condition will be used as a marker of filtering efficiency for each participant, and allow group comparisons to be made. If a group difference in this filtering efficiency is evident, the current task may also indicate the underlying cause of this variability: if the increased distractor processing is accompanied by a reduction in CDA amplitude under high cognitive load, this would suggest diminished visual working memory capacity. Conversely, if no such group difference in high load CDA amplitude accompanies the difference in filtering efficiency, then the pattern of results more likely indicate an increase in perceptual capacity (i.e. the ability to take in a greater amount of visual information) is driving the additional distraction. As such, the current study will elucidate the link between behavioural reports of increased perceptual capacity (Remington et al., 2012; Remington et al., 2009) and electrophysiological and behavioural markers of a standardised visual working memory capacity task.

Method

Participants

Forty-eight participants took part in the study (25 autistic adults and 23 non-autistic adults). The participants’ age ranged from 18 to 55 years. Participants were recruited through opportunity sampling such as social media, community contacts at the University College London’s Centre for Research in Autism and Education, autism support groups around London and the participant database of the University of London, Birkbeck. As this was the first study to address visual working memory capacity in autistic and non-autistic adults using CDA, I selected an opportunity sample of autistic and non-autistic adults. While participants were not excluded if they had additional neurological or psychiatric conditions, care was taken to assess the co-occurring diagnoses, as there is a known visual working memory differences indexed by the CDA in filtering inefficiency in conditions such as ADHD (Gu et al., 2018), depression (Owens et al., 2012) and capacity limits in high level of trait anxiety (Qi et al., 2014). Prevalence rates for epilepsy are higher in autism compared to the general population and estimates range from 5- 40% depending on age, cognitive abilities, and genetic bases for autism (e.g. Rett's or Fragile X syndrome, also see Canitano, 2007 for a review). Due to an increased risk for epileptiform abnormalities in the EEG recordings, epilepsy was an exclusion criterion for the study and all participants confirmed that they did not have epilepsy. All participants reported normal/corrected to normal vision and were native English speakers, this was important for the verbal IQ assessment.

All autistic participants had previously received a formal autism diagnosis from a qualified, independent clinician. A total of 15 participants were excluded: two in each group due to performance below chance, and four in each group due to excessive ocular and myogenic artefacts. For the excluded participants less than 40 trials per condition remained due to excessive artefacts and were therefore excluded from the sample. An additional 3 participants (n=1 from the autistic sample) were excluded due to excessive alpha wave activity. The final sample included 33 participants (see full demographics in Table 2).

An Autism Diagnostic Observation Schedule (ADOS-2, (Lord, Rutter, DiLavore, Riri, et al., 2012) was conducted to confirm the autistic participants' autism diagnosis. The ADOS-2 is a semi-structured, standardised assessment that rates the participant's language and communication, reciprocal social interactions, imagination and stereotyped behaviours and restricted interests in line with the diagnostic criteria of the DSM-V (Lord, Rutter, DiLavore, Riri, et al., 2012). The ADOS Module 4 has a good validity with sensitivity estimates ranging from 80.3-89.1% and specificity estimated of 62.1- 90.9% (Hus et al., 2014). All autistic participants met the clinical diagnosis for autism using the ADOS Module 4.

IQ scores were obtained using the Wechsler Abbreviated Scale of Intelligence, second version 2-subscale, (WASI-II, Wechsler, 2011). The test yielded three scores, the overall Full-Scale IQ (FSIQ-2) and the standard scores for matrix and vocabulary reasoning. Internal consistency for the FSIQ composite score is excellent (.94). The reliability, specifically test-retests reliability is at .90-96 and inter-rater reliability is excellent at .94-95 for vocabulary reasoning (McCrimmon & Smith, 2013). All participants scored above 80 in the vocabulary and matrix reasoning subtests. Groups were matched on matrix reasoning but not on vocabulary reasoning (see Table 2). Independent sample t-test confirmed that on average the groups did not differ significantly on the FSIQ-2 composite score.

All participants also completed the Social Responsiveness Scale, second edition (SRS-2; Constantino & Gruber, 2012), a validated and reliable 65-item scale used to assess self-reported autism traits. On a 4-point Likert scale (0=not true to 3=almost always true), the categories of restricted interests and repetitive behaviour and social aspects of awareness, cognition and communications were assessed. The scale has excellent test-retest reliability (.88-.95) and an interrater reliability of (.61-.92) and good internal consistency (α=.95; Bruni, 2014). For the autism group, the scores were all above 65 which indicates moderate to severe classification of the impact on everyday social interaction consistent with the SRS scores of the clinical population (Constantino & Todd, 2003). All non-autistic participants scored below the clinical threshold of 60, which suggests that none of the non-autistic participants showed autistic traits.

All participants filled in a background questionnaire containing questions regarding their demographics including ethnicity and additional clinical diagnoses (see Table 2).

Table 2. Descriptive statistics for the background variables of participants assessed on the background questionnaire, WASI-II, SRS-2, ADOS-2, STAI-T, DASS-21, ASRS by group

	Non-autistic (*n* =15)		Autistic (*n* =18)		
	M Range	(SD)	M Range	(SD)	*p*-value
Demographics					
Gender (M:F)	9:6		12:6		.70
Age (in years)	32.15	(10.31)	33.95	(10.63)	.63
	18 - 50		19 - 55		
FSIQ-2	118.93	(14.36)	111.59	(14.47)	.17
	89 - 140		85 - 139		
Verbal Reasoning	64.43	(10.72)	56.79	(9.13)	.05
	50- 80		41 - 71		
Matrix Reasoning	58.62	(7.97)	54.29	(8.26)	.18
	71 - 132		75 - 154		
SRS-2	38.8	(13.39)	96.78	(23.02)	<.001***
	17 - 59		65 – 140		
ADOS-2 severity score	-	-	8.84	(2.60)	-
Additional clinical diagnoses (frequencies)					
Attention deficit hyperactivity disorder	1		3		
Dyslexia	1		3		
Developmental coordination disorder	0		3		
Obsessive compulsive disorder (OCD)	0		2		
Borderline Personality Disorder	0		1		
Anxiety Disorder	1		10		
Depression	0		5		
Class of Medication					
ADHD	0		2		
Anxiety	1		3		
Antidepressants	0		4		
OCD	0		2		
Ethnicity					
Any White background	13		16		
Any Asian background	2		1		
Any Black background	0		0		
Any mixed background	0		1		
Other ethnic group	0		0		
Missing/ prefer not to say	0		0		

Note. FSIQ-2 = Full-scale IQ, 2 subtest version, derived from the Wechsler Abbreviated Scale of Intelligence, second edition (WASI-II; Wechsler, 2011), where mean score is 100 and standard deviation is 15; Verbal Reasoning T-scores derived from the WASI-II (Wechsler, 2011), where mean score is 100 and standard deviation is 15; Matrix Reasoning = t score, matrix reasoning index derived from the WASI-II (Wechsler, 2011); SRS-2 = t-score, calculated separately from the Social Responsiveness Scale, second edition *(SRS-2; John N. Constantino & Gruber, 2012)*; ADOS-2 = the Autism Diagnostic Observation Schedule, second edition *(Lord, Rutter, DiLavore, Risi, et al., 2012)*; *Any White background = White British, White Irish or any other White background; any Asian background = Chinese, Indian, Pakistani, Bangladeshi or any other Asian background; Any Black background = Black British, Black African, Black Caribbean or any other Black background; Mixed/multiple ethnic groups = Mixed White and Asian, Mixed White and Black African, Mixed White & Black Caribbean, Any other Mixed background.*

Measures

Additional questionnaires were used to quantify co-occurring ADHD, anxiety and depression. All questionnaires were filled in using the survey platform Qualtrics (Qualtrics, Provo, USA) and scoring was automated through the scoring system of the software.

Questionnaires

State-Trait Anxiety Inventory. Participants filled in the self-report State-Trait Anxiety Inventory, Trait Scale (STAI -T by Spielberger et al., 1983). The internal consistency ranged from .86 to .95 and has good test-retest reliability coefficients ranging from .65 to .75 over a 2-month interval (Spielberger et al., 1983). Participants made responses on a 4-point Likert scale (1=almost never, 2= sometimes, 3= often, 4= almost always). The scale was used as previous studies linked anxiety with reduced filtering efficiency and capacity (e.g., Eysenck et al., 2008, Owen et al., 2013). This is particularly important, as people with ASD have a high prevalence for anxiety disorders (Hollocks et al., 2014).

Depression and Anxiety Stress Scales. The Depression and Anxiety Stress Scales (DASS-21, Lovibond & Lovibond, 1995)***Brown, Chorpita, Korotitsch, & Barlow, 1997)*** was used as it is thought to reliably assess depression (α=.96), anxiety (α=.84) and stress (α=.93; Brown et al., 1997). The scales assess the acute symptoms "over the past week" with 7 items per subscale. Participants made responses on the 0-3 scale (0= Did not apply to me at all; 1= Applied to me to some degree, or some of the time; 2= Applied to me to a considerable degree or a good part of time; 3 = Applied to me very much or most of the time). Scores were multiplied by two, a score on the stress scale below 10 was classes as normal, on the anxiety and depression scale a score of 6 and 9 respectively were classed as normal. The scores were multiplied by 2, in line with the scoring manual of the DASS-21.

Adult ADHD self-report screener. Participants also completed an Adult ADHD self-report screener (ASRS-V1.1, Ustun et al., 2017) which is a validated clinical diagnostic tool that consists of 6 items to reliably assess ADHD symptoms in line with the DSM-5 ADHD diagnostic criteria. Participants respond on 5-point scale, (0 = Never, 1 = Rarely, 2 = Sometimes, 3 = Often, and 4 = Very Often) to questions such as *How often do you have problems remembering appointments or obligations*?. A high score on the scale indicates higher levels of ADHD traits. The scale measures inattentiveness on four items and hyperactivity and impulsivity on two items. The sensitivity of positively predicting ADHD is at .94 and for a negative prediction at 23.5 (Kessler et al., 2007). Internal consistency of items was high (Spearman's rho ranged between .61-.79) and Cronbach's alpha was fair at .54 for the total scale, .57 for the inattentiveness scale and .59 for the hyperactivity and impulsivity scale (Silverstein et al., 2018). The overall scale was test-re-test reliability of .78.

Sensory Perception Quotient. Participants completed the shortened Sensory Perception Quotient (SPQ; Tavassoli et al., 2014), a 35-item scale, that assess fundamental sensory experiences in autistic individuals without assessing affective and behavioural sensations across all sensory domains. The SPQ was developed to specifically Questions include, for example*, I would be the first to hear if there was a fly in the room*. Responses were given on a 4-point Likert-type scale (1 = strongly agree to 4 = strongly disagree). Low scores on the SPQ indicate sensory hypersensitivity. The SPQ shows excellent reliability (α = 0.93) and moderate concurrent validity (r = −0.49, p = 0.007) with the Sensory Over-Responsivity Scales (Schoen et al., 2008).

Experimental Task

Change Detection Task. A visual working memory task was adapted from Vogel et al. (2005) and was presented using E-Prime 3.0 (Psychology Software Tools Inc., Sharpsburg, PA, USA) on a 23 inch hp elite one800 desktop computer. The software controlled the experiment and collected the behavioural data. Participants' viewing distance was approximately 70 cm from the screen.

Participants were presented with target shapes and asked to memorise their orientation (memory array), followed by a test array when they were asked to indicate if the orientation of the target shapes had changed relative to the memory array. The rectangles were oriented at 0, 24, 90 or 135 degrees throughout the experiment and the fixation cross and the shapes presented at a visual angle of 2 degrees apart. The shapes appeared on the screen in a region of 4 x 7.2 degrees. The rectangles were separated by at least 2 visual angles.

The memory array consisted of two or four geometric target shapes that appeared bilaterally in one of three conditions: two red rectangles (low working memory load), four red rectangles (high working memory load), or two red and two blue rectangles (distractor condition). The colours of the experiment were based on (Vogel et al., 2005).

Each trial began with a fixation cross which was presented for 700ms on the screen alongside with an arrow above the fixation cross pointing to either the left or right side of the screen. The direction of the arrow was randomised, and indicated which visual field the participants was required to attend to for the memory and test array of the current trial (see Figure 9). An equal number of trials were presented in the left and right visual field. The memory array was then presented for 100ms, followed by a 900ms retention period.

Subsequently, the participants were presented with the test array that consisted of the same number of shapes as the memory array for 2000ms. Whether the orientation of one of the target shapes changed or not was randomly assigned, and both conditions were equally likely to occur. The participants responded using a keyboard to indicate whether the orientation of the shapes was identical to the memory array or not (participants “c”-key on the keyboard for change and “n”-key for no change). If responses were made before the end of the response phase, the next trial began. If participants did not respond during the test array (e.g., 2000ms), an omission was registered and the next trial began automatically.

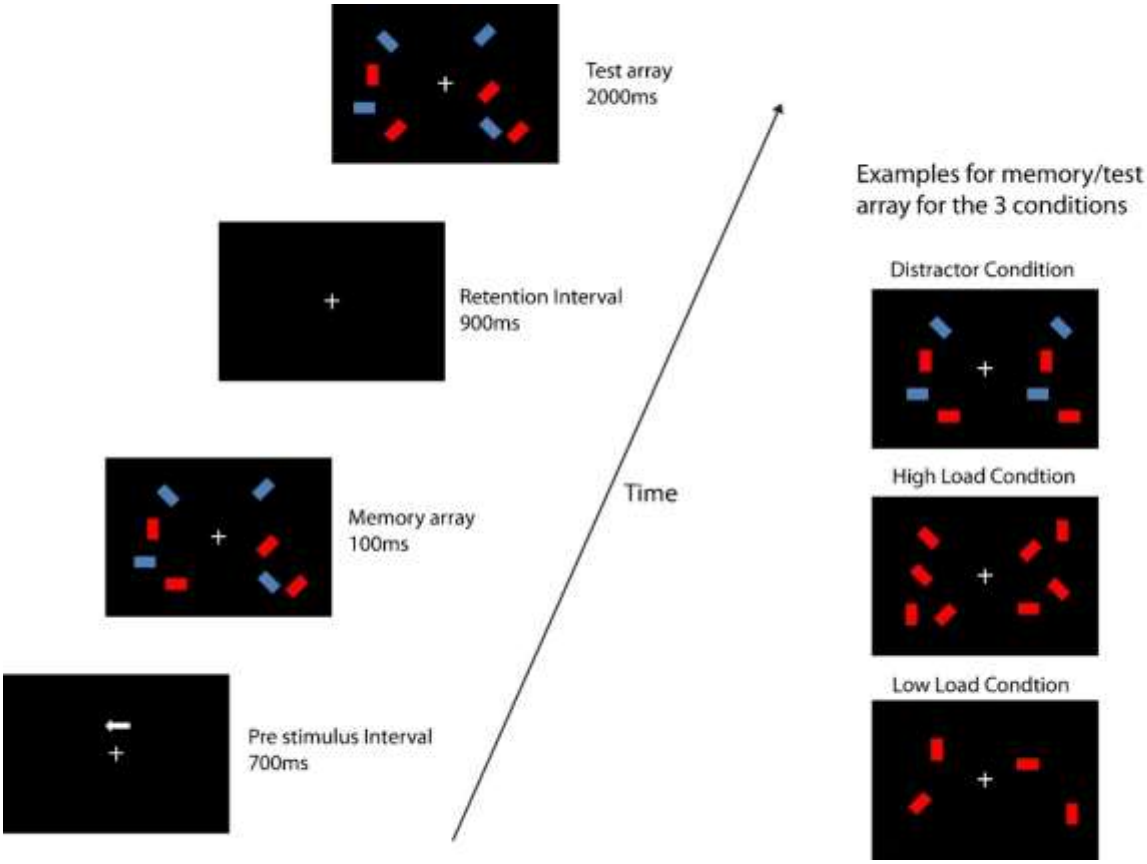


Figure 9. Depiction of an example trial from the Change Detection task and sample stimuli for the 3 experimental conditions. The trial example illustrates the distractor condition (targets= red shapes and distractors = blue shapes) with a change present (bottom left rectangle is rotated anticlockwise in test array).

Visual presentations of sample trials for each condition were used to explain the experimental task to all participants. In addition to visual stimuli, participants were required to read a summary of the experimental instructions. The experimenter verified that the participants understood the instructions, especially that only red rectangles had to be remembered and that the geometric shapes had to be memorised without shifting eye gaze away from the central fixation cross. The task began with a practice block where participants were presented with 36 trials and received feedback.

If the accuracy was below 50% during the practice block, the instructions were reiterated and participants repeated the practice block with feedback before completing the experimental blocks. The instructions and the practice block were repeated for one participant of each group. Participants were asked to sit as still as possible and to minimise eye blinks throughout the duration of the blocks. The experimenter stayed in the testing room with the participant to monitor performance, EEG activation and eye gazes throughout the duration of the task. Participants were encouraged to take breaks in between the blocks.

Subsequently, participants completed seven experimental blocks, each with 84 trials. Across trials, each condition equally likely to occur. No feedback was given during the experimental blocks. Brain activation was measured throughout the task using a BioSemi Active Two System (see below).

Procedure

Ethics approval for postgraduate research students was obtained from the Department of Psychology and Human Development, University College London, Institute of Education. All procedures were in accordance with the ethics code of the British Psychological Society. All participants gave informed written consent before starting the experiment.

Participants took part in the study at the research facilities of the University College London Campus in London. After participants gave informed consent, the WASI-II was administered and participants filled in the questionnaires. Subsequently, the EEG system was set up and participants performed the change detection task. Lastly, an ADOS was performed with the autistic participants. The study took between 3 and 3.5 hours and participants were reimbursed £8 per hour (n=30) or received course credits (n=3).

Data preparation

Behavioural data preparation. To assess performance on the change detection task, capacity scores (K, Pashler, 1988) were calculated using the following formula $K= S((H-FA)/(1-FA))$ for all three conditions. Where S is the number of items in the set size, H the proportion of correct detections (Hit rate) and FA the proportion of false alarms. This is based on recommendations for change detection tasks with the full set size at presented as the test array (i.e., whole-display recognition; Rouder et al., 2011). Thus, K corresponds to the average number of items that a participant can maintain. In the 2 target condition, a K score of 2 would reflect perfect K score, similarly, in the 4 target condition a K score of 4 would reflect perfect performance (e.g., hit rate of 1.0 and 0 false alarms). Therefore, a K score of 2.5 in the high load condition indicates that the average capacity was two and half items. Mean accuracy and reaction times were calculated for the different conditions for each participant. Repeated measure Analysis of Variances (ANOVAs) with group as between subject factor and load as within subject factor were performed on accuracy, reaction time and K score data. Correlation analysis for anxiety, depression, stress, ADHD and working memory load were also computed.

EEG data acquisition and Pre-processing of the EEG data. The participants were seated in an electronically shielded room with lighting switched off for the duration of the change detection task. Neural data were recorded through the BioSemi ActiveTwo system (BioSemi Amsterdam, The Netherlands) using the standard montage of the extended international 10/20 placement of the 64 electrodes in conjunction with the software Biosemi ActiView (Cortech-Solutions). The data were recorded at a sampling rate of 1025Hz. Additional external electrodes were used to record electro ocular activation. Horizontal eye movements, (horizontal electrooculogram HEOG) were recorded placing electrodes at the outer canthi of left and right eyes. The sampling rate was down sampled to 512 Hz with a bandpass filter of 0.01-30Hz (Offline Butterworth zero filter). No additional offline filters including high pass filters were applied due to potential influences of high pass filters on slow wave components (Tanner et al., 2015). The data was offline re-referenced to the left and right mastoids. Correct experimental trials were stimulus locked into 1100ms epochs from 100 ms before the onset of the memory array and continued for 1000ms. Artefacts in HEOG and vertical electrooculogram (VEOG) channels were rejected at 60mV and all electrodes were analysed for myogenic artefacts at ±80 µV with a 200ms/0.5mV gradient relative to the 100ms pre-stimulus baseline. On average 67 percent of the epochs were kept for the autistic participants and 73 percent epochs were kept for the non-autistic participants.

Event Related Potentials Contralateral Delay Activity and lateralised P1. The CDA utilises the contralateral organisation of the visual system. The contra and ipsilateral waveforms were calculated for both sides of the hemisphere and compared to the activation of the-to remembered- side. The CDA waveforms were calculated by averaging the signal over the occipital-parietal electrodes during the retention phase (400ms to 1000ms). Contralateral wave forms were averaged over the right hemisphere (PO8) in conditions where participants were cued with left pointing arrow presented in the centre of the screen. For conditions where to-be-remembered items were presented on the right side of the screen, activation was averaged over the electrodes on the left hemisphere (PO7). For ipsilateral waveforms, the activation of the right side was averaged when the right side was cued. The reverse was applied for the ipsilateral waveform for the left side (i.e. stimulus cued on left side and activation of the left visual cortex). The CDA was calculated between 400 and 1000ms after the onset of the memory array, during the retention interval.

The lateralised P1, an early sensory evoked potential related to spatial selective attention (Hillyard et al., 1998) is, similar to the CDA, a lateralised component (Clark &Hilliard, 1996) and was derived from the electrodes PO8 and PO7. The P1 was analysed from 80-150ms.

The mean amplitude for the P1 and CDA were entered as dependent variables into separate 2-way repeated measures ANOVAs with condition as a within-subject factor (3 levels: Low Load Condition, High Load Condition and Distractor Condition) and group as between-subject factor (2 levels: autistic and non-autistic adults). Additionally, for the CDA latency effects were analysed in 3-way ANOVAS with time (2 levels: early (400-700ms) and late (700-1000ms), condition (3 levels: Low Load Condition, High Load Condition and Distractor Condition) as within subject factor and group as between subject factor (2 levels: autistic and non-autistic adults). Further Pearson's correlations were performed to test the relationships between the mean questionnaire scores and capacity and filtering efficiency. All multiple comparisons were Bonferroni-corrected and Greenhouse-Geisser adjustments were made when sphericity assumptions were violated.

Results

Co-occurring conditions

Table 3. Descriptive statistics for the participants assessed on the STAI-T, DASS-21, SPQ, ASRS by group

	Non-autistic (*n* =17)		Autistic (*n* =19)		
	M	(SD)	M	(SD)	
	Range		Range		*p*-value
STAI-T	43.93	(10.37)	57	(8.85)	<.001***
	26 - 58		34 - 71		
DASS -21 Overall Score^{a}	28.53	(15.41)	50.22	(26.47)	<.001***
	8 - 60		12 - 98		
DASS-21 Depression	7.20	5.39	14.89	10.61	.03
	0 - 18		2-36		
DASS-21 Anxiety	7.33	5.38	13.67	9.36	.07
	0 - 16		4 - 36		
DASS-21 Stress	12.27	7.85	18.89	976	.08
	0-28		6-36		
SPQ	57.7	16.4	43.53	12.39	.01
	35 – 85		19 - 62		
ASRS	7.8	(2.96)	13.11	(2.83)	<.001***
	3 - 13		9 - 20		

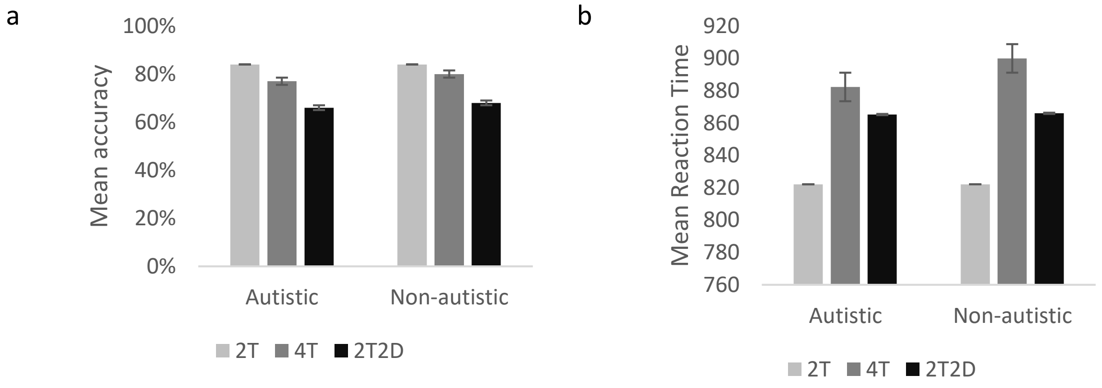
*Note. ***p<.001, all other results are not significant after Bonferroni correction; STAI-T (State-Trait Anxiety Inventory, Trait Scale; Spielberger et al., 1983), DASS-21 (Depression Anxiety, Stress Scales -21, (Brown et al., 1997), ^{a}missing data of 3 participants (missing data: not autistic=1, autistic=2), SPQ (Sensory Perception Quotient, Tavassoli, Hoekstra, & Baron-Cohen, 2014); ASRS (Adult ADHD self-report screener Ustun et al., 2017).*

Overall, the data were normally distributed, except for the depression and anxiety subscales of the DASS-21. To test whether the group differed on sensory processing, stress or ADHD symptoms, independent sample t-tests were performed as well as Mann-Whitney-U tests for the DASS-21 anxiety and depression subscale (see Table 3). Co-occurring psychiatric symptoms in autism are high, as expected, the autistic participants showed elevated symptoms for trait anxiety, total score of the DASS and ADHD traits were significantly elevated in the autism group. Participants did not significantly differ on the SPQ and anxiety subscales of the DASS-21 after correcting for the multiple comparisons using Bonferroni's α correction (.05/7= .007).

Behavioural Performance on Working Memory Task

Mean accuracy on the behavioural task was calculated for both groups at each level of load. As illustrated in Figure 10, a repeated measures ANOVA with group and load as factors yielded a significant main effect of load (*F*(2,62)=98.38; *p*<.001, η^2=.32), indicating that accuracy levels changed depending on load. There was no main effect of group and no interaction effect (*F*<1). Separate paired sample t-tests indicated that for both groups all three conditions were significantly different (*p*<.001). The accuracy was highest in the low load condition, reduced in the high load condition and lowest in the distractor condition, suggesting that the load manipulation was effective.

Figure 10. Mean Accuracy and Reaction Time for both Groups for each level of load



Note.a) mean accuracy b) reaction time as a function of group and condition, 2T = 2 targets, low load condition, 4T = 4 targets in the high load condition and 2T2D= 2 targets and 2 distractors in the distractor condition.

ANOVAs revealed a significant main effect of load on reaction time: the reaction time changed with load (*F*(2,62)=25.13, *p*<.001, η^2=.03), but no main effect of group or interaction between load and group (*F*<1; see Figure 10b). For both groups separate paired sample t-tests were performed and suggested that reaction times were faster in the low load compared to high load group (autistic sample: $t(17)=4.40$, $p<.001$; not autistic sample: $t(14)=-4.37$ $p=.001$, see means in Figure 10a). Similarly, the reaction time was significantly faster in the low load vs the distractor condition (autistic sample: $t(17)=4.08$, $p<.001$; not autistic sample: $t(14)=5.55$, $p<.001$). There was no statistical significant difference for reaction time in either of the groups between the high load and distractor condition (autism group $p=.27$; not autistic sample: $p=.054$).

Mean working memory capacity scores were calculated (see Figure 11) for the three conditions and group using Pashler's formula (Pashler, 1988). ANOVAs yielded a main effect of load on working memory capacity ($F(2,31)=11.4$, $p<.001$, $\eta^2=.08$) which suggests that working memory capacity was highest under the high load condition. The K score in the high load condition[4] was on average 1.64 (SD= 0.37) in the non-autistic sample and 1.44 (SD=.39) in the autistic sample which suggest that there was no ceiling effect in the study. There was no main effect of group ($F(1,31)=1.47$. $p=.23$, $\eta^2=.23$) or interaction between load on working memory capacity and group ($F<1$).

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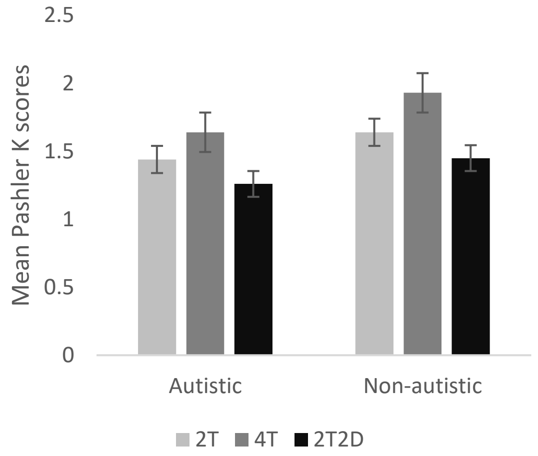
[4] Note that the K-score for the low load condition would be 2, in this context, the K-score for the high load condition for the 4 target condition is a more accurate measure of K.

Figure 11. Mean K-Scores for both Groups for each level of load



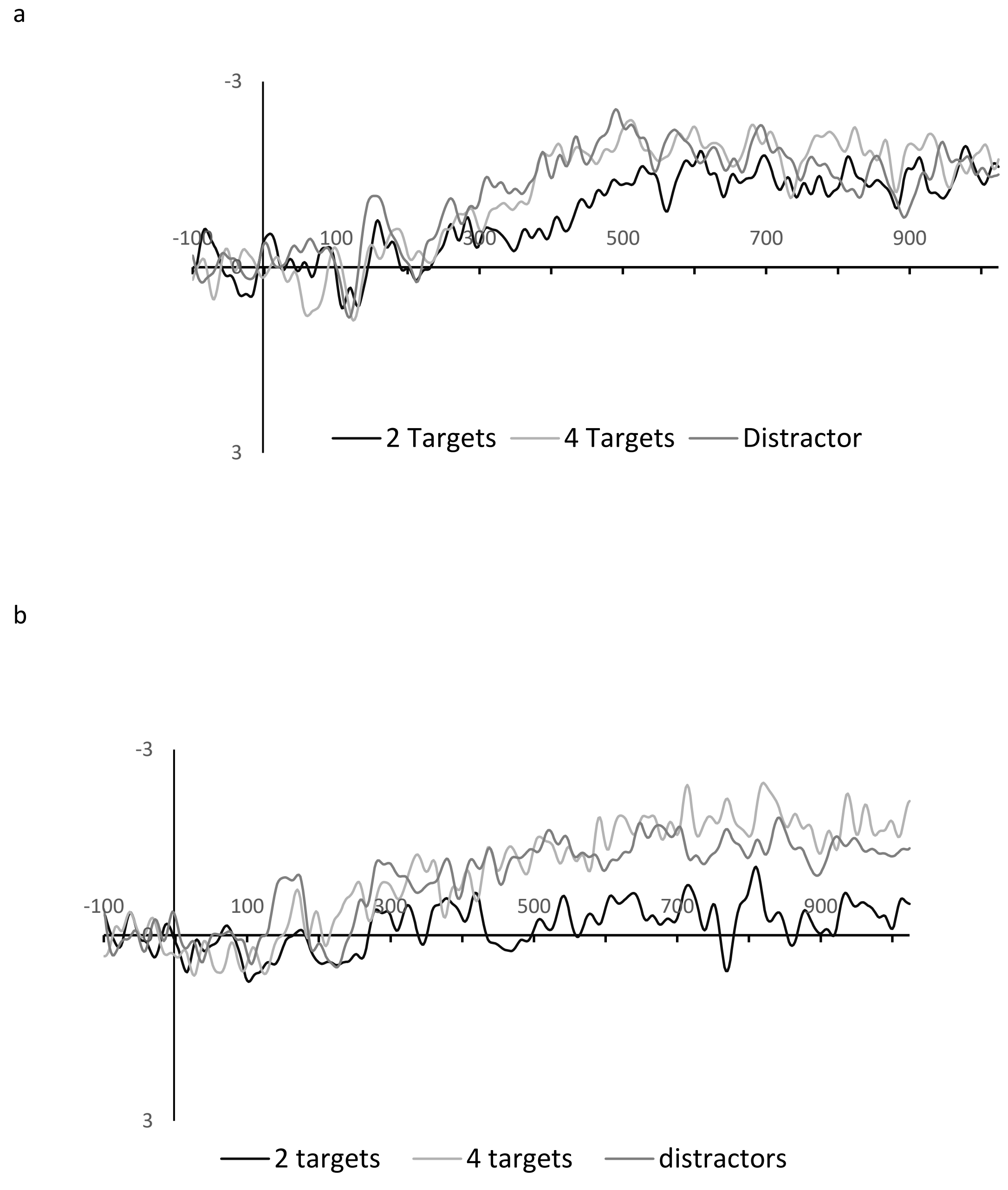
Note. 2T = 2 targets, low load condition, 4T = 4 targets in the high load condition and 2T2D= 2 targets and 2 distractors in the distractor condition.

Overall, the behaviour results indicate that the load manipulations were successful and there were no behavioural differences in accuracy, reaction time or working memory capacity between the groups. The accuracy scores indicate that participants appear to be less accurate when filtering out additional information in the distractor condition compared to the high and low load condition. However, K-values seem to be similar for the distractor condition to the low load condition which suggest filtering efficiency (and the ability to ignore the task irrelevant information).

Event-related potentials

The averaged contralateral and ipsilateral activity for the parietal occipital electrodes PO8 and PO7 illustrate the time locked time window from -100 to 1000ms in Figure 13. The memory array was presented at 0ms to 100ms. The grand averaged difference waves are presented in Figure 12. Mean amplitude data were entered into the analysis to examine differences in spatial attention (lateralised P1), working memory (CDA). Visual inspections of the grand averaged difference waves suggest differences in the latencies between the groups in the lateralised P1 and the CDA. Jackknife analysis (e.g. Kiesler, 2008) to specify latency differences were performed, however, there was no clear onset of the CDA amplitude in the autism group. Therefore, the mean amplitude for the time window of 400-500ms was selected to test if there were any significant group differences.

Figure 12. CDA waveforms for the low load (black), high load (light grey), and distractor condition (medium grey) for the non-autistic adults (a), and the autistic adults (b) stimulus onset starts at 0 ms for 100 ms



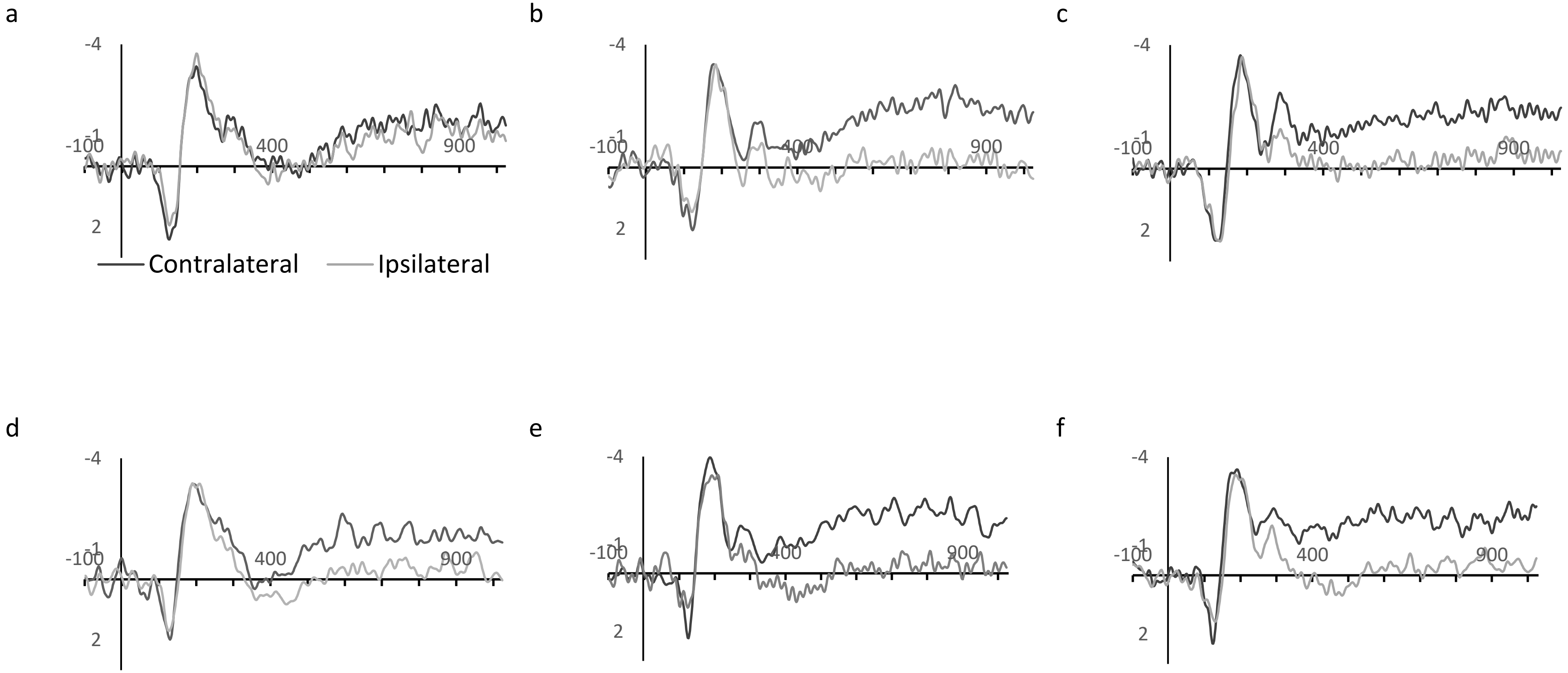


Figure 13. Ipsi- and contralateral waves for the autism group in (a) the low load condition (b), high load condition and (c) the distractor condition and the non-autistic sample for the (d) low load condition, (e) the high load condition and (f) the distractor condition.

Table 4. Mean Amplitudes and Standard Deviations for the lateralised P1 and CDA for both groups by condition

		Low load		**Distractor Condition**		**High Load**	
		Mean	(SD)	Mean	SD	Mean	(SD)
P1 (80-150ms)	Autistic	.46	(1.07)	-.14	(1.45)	.33	(1.68)
	Not autistic	.16	(.93)	-.11	(1.45)	.19	(1.44)
Early CDA (400-500ms)	Autistic	-.30	(1.74)	-1.20	(2.57)	-1.37	(1.65)
	Non-autistic	-.81	(1.20)	-1.77	(2.15)	-1.93	(1.43)
CDA (400-1000ms)	Autistic	-.29	(1.71)	-1.66	(2.48)	-1.39	(1.73)
	Not autistic	-1.62	(1.89)	-1.17	(2.08)	-1.39	(1.66)

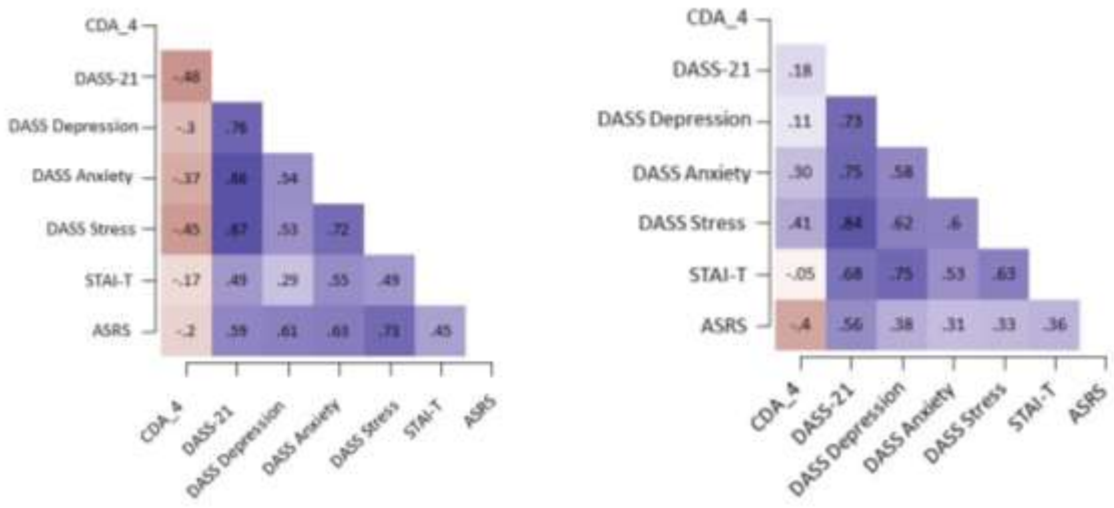
Lateralised P1. To understand the allocation of spatial attention to the cued side the lateralised P1 component was analysed. The mean amplitude for the time window of 80-150ms (based on mean activation at the electrodes PO7/PO8) for the P1 were calculated for both groups. The ANOVA revealed no significant main effects or interactions (*F*s<1). This suggests that there were no significant differences in early allocation of selective attention between the groups (for means and standard deviations see Table 4).

CDA. Inspections of the difference wave in Figure 12 suggest a different latency trajectory for the CDA between 400 and 500 ms in the autism group. Therefore, a mixed ANOVA with the time window between 400 and 500ms were carried out with group as a between-subjects factor and load as a within-subjects factor. There was a significant main effect of load (*F*(2,62) = 5.17, *p*<.001), suggesting that the amplitude changed with load (see Table 4). There was no main effect of group and the interaction was not significant (*F*s<1). This suggests that there were no significant differences in the onset of the CDA amplitude. To investigate differences in visual working memory load between high and low levels of load on the mean CDA for the time window between 400 and 1000ms, a 2x2 mixed ANOVA was conducted with group as a between subject factor and load as a within subject factor (high and low load). The ANOVA revealed no main effect main effect of load (*F*(1,31)=1.22, *p*=.28, η^2=.01) or group (*F*<1). However, the significant interaction between load and group (*F*(1,31)=4.68, *p*=.04, η^2=.05) was significant. This suggests that in the non-autistic sample there was no difference between the high load and low load conditions (*t*(14)=.63, *p*=.54), which indicates that the capacity limit was reached at set size 2. In the autism group the CDA amplitude in the autism group was significantly larger for the high load condition than for the low load condition (*t*(17)=2.78, *p*=.01). Importantly, this indicates that autistic participant’s capacity was larger at high levels of load and suggest an increased visual working memory capacity in the autism group.

To test visual working memory storage efficiency the mean CDA was averaged for the time window between 400 and 1000ms. Mixed ANOVAs were conducted with group as a between subject factor (2 levels: autistic vs non-autistic) and load (3 levels: low, high and distractor conditions) as between-subject factors were entered into the analysis. There was no main effect of load or group (*Fs*<1). The interaction between load and group was not significant (*F*(2,62)= 2.90, *p*=.06, η^2=.04). Separate follow-up ANOVAs were carried out for both of the groups to test whether there were significant differences between the levels of load. For the non-autistic sample, the CDA amplitude was not significantly different at across different levels of load (*F*<1, see Table 4 for means and standard deviations), which suggests that the capacity was reached at set size two in the low load condition. There was however a significant difference in the autism group (*F*(17)=3.98 *p*=.03, η^2=.19), suggesting that the CDA amplitude was significantly larger in the high load condition compared to the low load condition (*t*(17)=2.78, *p*=.01). There were no differences between the distractor condition and the high load condition (*t*(17)=.56, *p*=.58) and the difference in the CDA amplitude at low load and distractor condition did not reach significance (*t*(17)=1.95, *p*=.07).

Further Exploratory Correlations. As previous studies have shown that anxiety, depression and ADHD are thought to alter visual working memory as measured in the CDA, non-parametric correlations between the CDA amplitude for the high levels of load condition (400-1000ms time window), and the STAI, ASRS and DASS (including subscales) were performed for both groups. The heatmap in Figure 14 shows that as expected, the self-report measures for trait anxiety, depression and ADHD symptomatology are highly positively correlated for both groups. There were, however, no significant correlation between self-report measures and the CDA amplitude, which suggests that neither anxiety, depression, stress, ADHD symptomatology nor sensory processing are associated with the CDA amplitude and related to an increased capacity limit in the autistic sample

Figure 14. Spearman's rho heatmap for the CDA amplitude at high levels of load (set size 4) and the self-reported DASS-21, ASRS, STAI-T for the non-autistic sample (left panel) and the autistic sample (right panel)



*Note. ***p<.001, **p<.01, *p<.05; STAI-T (State-Trait Anxiety Inventory, Trait Scale; Spielberger et al., 1983), DASS-21 (Depression Anxiety, Stress Scales -21, Brown et al., 1997), ASRS (Adult ADHD self-report screener Ustun et al., 2017), CDA_4 = CDA amplitude at set size 4.*

Discussion

The present study investigated if, and how, autistic and non-autistic adults differ in aspects of selective attention such as visual working memory capacity and filtering efficiency. For this purpose, I assessed the CDA amplitude, an index of visual working memory capacity on a standardised visual working memory task (similar to Vogel et al.'s, 2005 change detection paradigm). Based on previous work on increased perceptual capacity in autism, I predicted that visual working memory capacity would also be increased in autism. Crucially, in line with the hypothesis, autistic participants showed an increased visual working memory capacity as measured on the CDA, compared to the non-autistic sample that appears to be reaching the capacity limit at set size 2. Importantly, these differences were not present at the behavioural performance level. There were no significant performance differences between the groups and no evidence at the low load or the distractor condition which suggest that there were no differences in filtering efficiency across the groups.

An Increased Visual Working Memory Capacity in Autism. The preliminary results presented here suggest that autistic people have an enhanced visual working memory capacity. These findings directly relate to the behavioural findings of an increased perceptual capacity in autism (Remington et al., 2009; Remington et al., 2012), which suggest that autistic participants process more perceptual information in parallel. This is consistent with the sensory recruitment theory, which suggests that visual working memory and perceptual tasks show similar activation in the visual cortex. Taken together the findings from perceptual capacity studies and the present study provide evidence that visual working memory load leads to similar activation. However, Dunn et al. (2016) investigated visual maintenance in a sample of participants with high levels of autistic traits and did not find differences in SPCN amplitude on a spatial attention task. Their task, however, did not load on visual working memory capacity and the load remained at a set size of 2 throughout the task. Therefore, this is the first study that provides evidence for an increased visual working memory capacity in autistic adults.

Distractibility and Filtering in Autism

The increased perceptual capacity has been reported to come at the detriment of increased distractor processing if the task relevant information does not fill the perceptual capacity. This is in line with ERP studies and fMRI evidence that suggest that autistic people show increased levels of distractibility (Adams & Jarrold, 2012; Keehn et al., 2016, 2017; Murphy et al., 2014b). Given the previous literature on distractibility in autism and that the cost of increased perceptual capacity, it is surprising that in the present study, based on the ERP and behavioural evidence, there is no difference in filtering efficiency across the groups. While visual inspections of the difference wave in Figure 12 suggests that the CDA amplitude for the distractor condition was more similar to the high load condition in the autism groups (indicating reduced ability to filter out irrelevant information), the CDA amplitude in the present study for the low load and distractor condition was trending towards significance (p=.07). Thus, it is vital for future studies to follow up on the findings and explore distractibility in autism further to better understand how autistic participants can be efficiently supported (e.g. by reducing distracting information in the environment). It is also important to compare the findings to a non-autistic sample with high and low working memory capacity levels (e.g. as seen in Owens et al., 2012).

As outlined in chapter 1, the visual working memory literature in autism has produced mixed results for behavioural findings. Importantly, the present study highlights the importance of combining electrophysiological and behavioural measures. Whilst visual working memory capacity was increased, there was no detriment to filtering efficiency compared to the control group. It is therefore crucial to rethink the current visual working memory literature in autism. Visual working memory is crucial in a number of every day contexts such as work and educational settings. Having an increased visual working memory capacity may help to process more information in parallel. As such increasing visual working memory load might also help to improve educational outcomes. One recent study found that maximising perceptual load in autism can help to improve autistic people learn in a computerised classroom study (Remington et al., 2019). Current education practice often involves reducing information in the education environment for autistic participants, however, autistic people may have the ability to process more extra information instead. Capitalising this extra visual working capacity might help autistic people to maximise learning and could also improve performance in the workplace.

Limitations.

Whilst the CDA amplitude was increased in the autism group, there was no such corresponding behavioural finding based on the visual working memory capacity score K. One would have expected K to be increased along with an increased CDA amplitude, particularly when measuring K within the four-item high load condition. Previous studies have found a strong relationship between performance in the change detection task as measured in K and the CDA amplitude (e.g. Vogel & Machizawa, 2004). However, other studies with clinical samples did not report a correlation between K and the CDA amplitude (e.g. Wiegand et al., 2016), which could suggest an important dissociation and that K-scores may be influenced by other factors such as cognitive effort or strategies particularly within a clinical sample. In addition, the effect size for the interaction of group by load for the mean CDA amplitude was small (.05), which could suggest that this marginal interaction may be unreliable. As such, the current findings of this study required further assessment.

In the present study behavioural and EEG data was assessed at set size 2 and 4, and it is therefore unclear if the visual working memory capacity has reached asymptote for the autism group at set size 4. Indeed, previous findings from perceptual capacity studies have included multiple set sizes up to 6 targets that showed that autistic participants effectively process capacity limits (Remington et al., 2012). It is important to understand the capacity limits fully to support autistic people's visual perceptual and working memory capacity and fill it with task relevant information to avoid distraction. Therefore, in chapter 4, the findings of an enhanced visual working memory capacity are tested on a similar change detection task by adding an increased number of set sizes. This is specifically important as increased levels of processing are thought to be closely related to overwhelming sensory experiences that autistic people often report, which can be extremely debilitating and painful experiences (Jones et al., 2003; A. E. Robertson & Simmons, 2015). Therefore, it is crucial to better understand the capacity limits and filtering efficiency in autism to effectively support autistic people. In Chapter 4, a second paradigm is included to assess perceptual capacity that is set up resembling the change detection task. Subitizing is thought to be a marker of perceptual capacity (Eayrs & Lavie, 2018). Therefore contrasting the abilities in a subitizing and change detection task allows to draw direct comparisons between the tasks and perceptual and visual working memory capacity.

Chapter 4

Contrasting Visual Working Memory Capacity and Perceptual Capacity

Chapter 3 investigated visual working memory capacity and filtering efficiency in a standardised visual working memory task in autistic and non-autistic adults. I examined the electrophysiological and behavioural markers of visual working memory capacity and filtering efficiency. In chapter 3 there was preliminary evidence of an enhanced visual working memory capacity in autism. As the effect sizes were small and it is unclear whether autistic people reached asymptote at set size 4, thus, the present chapter will investigate visual working memory capacity further. In conjunction with a visual working memory task, a perceptual capacity task that has a qualitatively similar paradigm organisation to allow for the two capacity limits to be directly contrasted. Therefore, in Chapter 4 I seek to directly compare perceptual capacity and visual working memory in autistic adults. A standardised change detection task based on Vogel & Machizawa's (2004) paradigm is used to complement the findings of chapter 3 and use it as a marker for visual working memory capacity. In addition, a subitizing task as a measure of perceptual capacity is used in this chapter, which has been used in the previous literature in the context of the Load Theory and shown to be a reliable marker of capacity (Eayrs & Lavie, 2018).

A number of previous behavioural studies have assessed subitizing ability/capacity in autistic individuals, with contradictory results. Some studies have reported that young autistic people show increased response times during subitizing, (Gagnon et al., 2004; Mottron et al., 2006; O’Hearn et al., 2013), reduced subitizing capacity across childhood, adolescence and adulthood (O’Hearn et al., 2013), while others have found no differences in behavioural performance when testing autistic adults (O’Hearn et al., 2016) compared to non-autistic adults. However, performance differences on the task have typically been evident when exposure times were long enough to enable participants to potentially count the visual information overtly, rather than assessing implicit ability to individuate objects. In support of this claim, while O'Hearn and colleagues (2016) did not find behavioural differences in autism within a subitizing task, they investigated the underlying neurophysiology of a subitizing task using fMRI, and identified that areas such as the parietal lobe were more active among autistic participants, which may suggest a counting strategy rather than direct differences in subitizing ability (O'Hearn et al., 2016). Importantly, this potential confound is overcome within ERP methodology. The N2pc provides a real time online measure of early and rapid attentional selection of multiple objects in parallel. Thus, the N2pc should be unaffected by any post-perceptual strategy in counting objects during long exposure durations or processed information within working memory.

To the best of my knowledge, this is the first study that aims to directly compare perceptual and visual working memory capacity using EEG as well as behavioural measures with an autistic sample. Based on previous evidence, I hypothesised that perceptual capacity would be enhanced in the autistic group, as evidenced by the N2pc reaching an asymptote at a higher set size level compared to the control group. Regarding visual working memory capacity, based on the results of chapter 2, a similar finding should also be observed on the CDA component indicating higher capacity in the autistic sample. Finally, perceptual and visual working memory capacity can be directly compared, with the hypothesis that the degree to which autism modulates perceptual capacity should be qualitatively similar to that of items in visual working memory (e.g. a two-item increase within both subitizing and change detection tasks).

Method

Participants

Forty-three participants (20 autistic and 23 non-autistic adults, aged 19 to 45) took part in the EEG study at the University College London (UCL) Institute of Education. Participants were recruited through opportunity sampling such as social media, community contacts at the UCL Centre for Research in Autism and Education, autism support groups around London, personal contacts of the researchers and the participant database of the University of London, Birkbeck. As this is the first study to address visual working memory capacity and subitizing capacity in autistic and non-autistic adults we selected an opportunity sample, without excluding participants for co-occurring conditions such as ADHD, mental health disorders or medication taken in either of the samples. Care was taken, however, to assess and document these co-occurring health conditions. Exclusion criteria were epilepsy and Fragile X syndrome. Due to excessive eye-movements four autistic and five non autistic participants were excluded from the analysis (see EEG analysis section for more details). One autistic participant terminated the study early and was excluded from the sample. Therefore, the final sample included 34 participants, of which 15 participants were autistic and 18 non-autistic (see

Table 5. Demographic information and scores on background variables assessed for further details). Due to the COVID-19 pandemic recruitment of further participants was not possible. As previous EEG studies do not report effect sizes, other studies in autism with perceptual capacity have been consulted for the effect sizes. Remington et al. (2012) reported a large effect size involving an interaction between group and detection sensitivity across four different set sizes ($\eta p^2 = .91$), with a sample size of 16 in each group. The study was therefore sufficiently powered.

All autistic participants reported having received a formal autism diagnosis from a qualified, independent clinician (DSM-IV-TR; APA, 2000a, or DSM-5; 2013a), or The International Classification of Mental and Behavioural Disorders, tenth edition (ICD-10; WHO, 1992). The diagnostic criteria were confirmed using the social responsiveness scale (SRS-2, Constantino & Gruber, 2012). All autistic participants met the clinical threshold suggestive of an autism diagnosis on the SRS-2 (*t*-scores above 60) and none of the non-autistic participants scored above the clinical threshold. Autistic participants also completed an Autism Diagnostic Observation schedule (ADOS-2, (Lord, M Rutter, et al., 2012) to confirm their autism diagnosis. ADOS data was not available for one participant, however, the participant met the clinical threshold for the SRS-2.

IQ scores were obtained using the Wechsler Abbreviated Scale of Intelligence, second version 2-subscale, (WASI-II, Wechsler, 2011). The test yielded three scores, the overall Full-Scale IQ (FSIQ) and the standard scores for matrix and vocabulary reasoning. Internal consistency for the FSIQ composite score is excellent (.94). The reliability, specifically test-rests reliability is at .90-96 and inter-rater reliability is excellent at .94-95 for vocabulary reasoning (McCrimmon & Smith, 2013). All participants scored above 80 in the combined vocabulary and matrix reasoning subtests. Groups were matched on matrix reasoning and vocabulary reasoning (see Table 5). Independent sample t-test confirmed that on average the groups did not differ significantly on the FSIQ-2 composite score.

Table 5. Demographic information and scores on background variables assessed

	Non-autistic (*n* =18)		Autistic (*n* =15)		
	M	(SD)	*M*	(SD)	
	Range		Range		*p*-value
Demographics					
Gender (M:F)	7:11		11:4		**<.001*****
Age (in years)	8.31	(6.64)	29.16	(8.14)	.744
	19 – 45		19 - 39		
FSIQ-2[a]	11.41	(16.33)	115.53	(13.4)	.445
	89 – 141		93 – 143		
Verbal Reasoning[b]	9.58	(8.35)	59.26	(9.15)	.918
	45 – 76		41 - 80		
Matrix Reasoning[c]	52.58	(9.68)	57.80	(8.99)	.126
	38 – 71		36 - 73		
SRS-2[d]	35.33	(17.18)	100.8	(21.18)	**<.001*****
	6 – 58		65 – 147		
ADOS-2 severity score[e]	-	-	7.49	(2.70)	-
OSPAN[f]	54.06	(16.84)	47.17	(18.89)	.30
	(18-75)		(14-74)		
Co-occurring neurodevelopmental conditions (frequencies) n (%)					
ADHD	0	(0)	3	(20)	
Dyslexia	1	(5.5)	1	(6.6)	
Dyspraxia	0	(0)	6	(40)	
Learning disability	0	(0)	1	(6.6)	
Mental Health conditions (frequencies)					
Depression	0	(0)	6	(40)	
Anxiety	0	(0)	9	(59.4)	
Obsessive Compulsive Disorder	0	(0)	1	(6.6)	
Eating Disorder	1	(5.5)	1	(6.6)	
Class of Medication (frequencies)					
Stimulants to treat ADHD	0	(0)	2	(13.2)	
Antidepressants	0	(0)	4	(26.4)	
Ethnicity (frequencies)					
Any White background	7	(38.88)	12	(79.2)	
Any Asian background	6	(33.33)	2	(13.2)	
Any Black background	4	(22.2)	0	(0)	
Any mixed background	1	(5.5)	1	(6.6)	
Other ethnic group	1	(5.5)	0	(0)	

Note. [a]FSIQ-2 is a subscale from WASI-II (Wechsler, 2011) the score is derived from vocabulary and matrix reasoning, where mean score is 100 and standard deviation is 15; [b]Verbal Reasoning T-scores derived from the WASI-II (Wechsler, 2011); [c]Matrix Reasoning = t score, matrix reasoning index derived from the WASI-II (Wechsler, 2011); [d]SRS-2 = t-score, calculated separately from the Social Responsiveness Scale, second edition (SRS-2; Constantino & Gruber, 2012); [e]ADOS-2 = the Autism Diagnostic Observation Schedule, second edition (Lord, Rutter, DiLavore, Riri, et al., 2012), [f]OSPAN= automated operation span task (Unsworth et al., 2005). For ethnicity: Any White background = White British, White Irish or any other White background; Any Black background = Black British, Black African, Black Caribbean or any other Black background; any Asian background = Chinese, Indian, Pakistani, Bangladeshi or any other Asian background; Mixed/multiple ethnic groups = Mixed White and Asian, Mixed White and Black African, Mixed White & Black Caribbean, Any other Mixed background.

Measures

A range of experimental and self-report background questionnaires were completed by the participants. More details can be found in the next sub-section on self-report background measures and experimental tasks.

Background Measures.

Additional questionnaires were used to quantify co-occurring ADHD, anxiety and depression traits. All questionnaires were filled in using the survey platform Qualtrics (Qualtrics, 2020).

Colour Vision Test. All participants completed the Ishihara colour Vision Test that screens for the most common form of inherited colour vision deficiency (red-green; Ishihara, 1987) to ensure that participants were able to effectively distinguish the stimuli presented in the visual working memory and subitizing task. None of the participants had issues identifying the number presented in the colour vision test.

Demographic information. According to a short self-report questionnaire that was administered to assess basic demographic information and prior clinical diagnoses, autistic participants (n=8) reported one or more additional diagnoses of attention deficit hyperactivity disorder (ADHD), dyslexia, developmental coordination disorder or Learning Disability. One non-autistic participant reported an additional diagnosis of dyslexia. Ten additional diagnoses were mentioned by autistic participants (multiple diagnoses were possible) and one non-autistic participant reported underlying mental health conditions (see Table 5) for frequencies of the co-occurring conditions). Six autistic participants reported that they took daily medication for ADHD and/or mood stabilisers. Participants were not required to discontinue taking their medication prior to participating in the study. The autistic participants were less ethnically diverse compared to the non-autistic participants.

State-Trait Anxiety Inventory. Participants filled in the self-report State-Trait Anxiety Inventory, Trait Scale (STAI -T by Spielberger et al., 1983). The internal consistency ranged from .86 to .95 and has good test-retest reliability coefficients ranging from .65 to .75 over a 2-month interval (Spielberger et al., 1983). Participants response on a 4-point Likert scale (1=almost never, 2= sometimes, 3= often, 4= almost always). The scale was used as previous studies linked anxiety with higher levels of perceptual capacity (Berggren & Derakshan, 2013). This is particularly important, as people with ASD have a high prevalence for anxiety disorders (Hollocks et al., 2014). High scores on the STAI-T indicate high levels of anxiety.

Depression and Anxiety Stress Scales. The Depression and Anxiety Stress Scales (DASS-21, Lovibond & Lovibond, 1995) was used as it is thought to reliably assess depression (α=.96), anxiety (α=.84) and stress (α=.93; Brown et al., 1997). The scales assess the acute symptoms “over the past week” with 7 items per subscale. Participants made responses on the 0-3 scale (0= did not apply to me at all; 1= Applied to me to some degree, or some of the time; 2 = Applied to me to a considerable degree or a good part of time; 3 = Applied to me very much or most of the time). High scores on the DASS-21 indicate high levels of anxiety, depression and/or stress. The scores were multiplied by 2, in line with the scoring manual of the DASS-21.

Adult ADHD Self-report Screener. Participants also completed an Adult ADHD self-report screener (ASRS-V1.1, (Ustun et al., 2017) which is a validated clinical diagnostic tool that consists of 6 items to reliably assess ADHD symptoms in line with the DSM-5 ADHD diagnostic criteria. Participants respond on 5-point scale, (0 = Never, 1 = Rarely, 2 = Sometimes, 3 = Often, and 4 = Very Often) to questions such as *How often do you have problems remembering appointments or obligations?*. A high score on the scale indicates higher levels of ADHD traits. The scale measures inattentiveness on four items and hyperactivity and impulsivity on two items. The sensitivity of positively predicting ADHD is at .94 and for a negative prediction at 23.5 (Kessler et al., 2007)***.*** Internal consistency of items was high (Spearman’s rho ranged between .61-.79) and Cronbach’s alpha was fair at .54 for the total scale, .57 for the inattentiveness scale and .59 for the hyperactivity and impulsivity scale (Silverstein et al., 2018). The overall scale was test-re-test reliability of .78*.*

Sensory Perception Quotient. Participants also completed the shortened Sensory Perception Quotient (SPQ; Tavassoli et al., 2014), a 35-item scale, that assess fundamental sensory experiences in autistic individuals without assessing affective and behavioural sensations across all sensory domains. The SPQ was developed to specifically Questions include, for example*, I would be the first to hear if there was a fly in the room*. Responses were given on a 4-point Likert-type scale (1 = strongly agree to 4 = strongly disagree). Low scores on the SPQ indicate sensory hypersensitivity. The SPQ shows excellent reliability ($\alpha = 0.93$) and moderate concurrent validity ($r = -0.49$, $p = 0.007$) with the Sensory Over-Responsivity Scales (Schoen et al., 2008).

Experimental Tasks

E-prime 3.0 (Psychology Software Tools, Inc., Pittsburgh, PA) was used to execute the experiment, which was presented on a 23 inch hp elite one800 desktop computer. Three computerised tasks were presented measuring change detection, subitizing and an automated operation span task. The tasks will be explained in more detail in the present section.

Viewing distance was approximately 70 cm from the screen. All the responses were made via dedicated keys on the keyboard. The change detection and subitizing tasks were lateralised paradigms, with presentations in the left and right visual field. The centre of the task was marked by a white fixation dot (0.14 x 0.14° of visual angle) in the centre of the screen, which was presented throughout each trial. Participants were instructed to maintain their focus on the centre of the screen. The background for the experimental tasks was black, and the stimuli were dots with a size of 0.43 x 0.43°. The colours of the stimuli were red, pink, orange, blue, green, grey and turquoise. All colours were matched in luminance (4 cd/m2). The dots were presented in an invisible grid of 5x8 coordinates and never appeared directly adjacent to one another horizontally or vertically, but could appear adjacent diagonally. All other possible arrangements of stimuli within the 5x8 grid were possible and randomly selected on each trial. Because of this, items appeared at varying eccentricities. Before starting each of the experimental tasks, participants were shown a visual representation of the task (see Figure 15). Participants were encouraged to respond as quickly and accurately as they could.

Change Detection Task. The visual change detection task was similar to that of Vogel and Machizawa (e.g. Vogel & Machizawa, 2004) and was used to assess the visual working memory capacity in autistic and non-autistic participants. Each trial began with presentation of a fixation dot for 1000ms. Subsequently, a number of coloured target dots (a selection of six possible colours, depending on set size) were presented randomly on the left or right side of the screen for 100ms. The set sizes varied between 2, 3, 4 and 5 items, to test capacity limits as participants typically perceive approximately 4 items (Vogel & Machizawa, 2004). On the side that was to be ignored the same amount of grey distractor items were presented simultaneously. Participants were asked to memorise the colour of the objects for 600ms. Subsequently, participants viewed a memory probe array in which in 50% of the trials a change in one of the coloured dots occurred. Participants indicated on the keyboard whether they perceived a change in the memory probe or not. Participants had up to 2000ms to log their response on the keyboard. The target and distractor items for memory and test array were presented with a minimum distance of 2 degrees to the central fixation. Participants completed a short practice block and 18 experimental with 32 trials per block with a total of 594 trials. The task took around 40 minutes to complete.

Subitizing task. The subitizing task was similar to previous subitizing paradigms (see Ester et al., 2012; Pagano et al., 2014, for similar paradigms). The task was presented on a black screen and each trial began with an interstimulus interval of 1000ms. Subsequently, the subitizing array was presented for 100ms. The array consisted of green and red dots. On each trial participants saw 12 dots on each side of the screen. On the to-be-remembered side, between 2 and 6 red target dot were presented in a random order, the remaining dots were displayed in green. In the opposite hemisphere, 12 green dots were presented simultaneously. Set sizes from two to six were chosen in order to assess the point when the participant's subitizing capacity was reached (typically thought to be between three to four items, Vogel & Machizawa, 2004). The maximum set size (set size = 6) was increased compared to the change detection task to avoid inflation on set size 5 as participants tend to guess at the maximum set size (e.g. Eayrs & Lavie, 2018). This effect typically leads to increased performance on the maximum set size, hence why set size 6 was added to the subitizing task. The presentation of an equal number of dots in both hemispheres is required for ERP designs to avoid a possible sensory contamination of the lateralised N2pc. In addition, if only the numerosity of the target dots and the same amount of contralateral dots had been presented, participants could have not have to shifted their attention across trials and still indicate the correct number of targets/non-targets, this would have contaminated the calculation of the lateralised potential of the N2pc. Therefore 12 dots were presented at all times on the screen with varying numbers of targets and non-target colours included in the presentation depending on the set size.

After a 600ms delay with just the centre fixation presented, question marks appeared above and below the centre fixation and participants had 3000ms to indicate how many target dots they saw on the screen. Participants logged their responses using the number keys on the keyboard. Participants completed a total of 720 trials across 18 blocks with 40 trials per block and a short practice block with 12 trials. The task took approximately 35 minutes to complete.

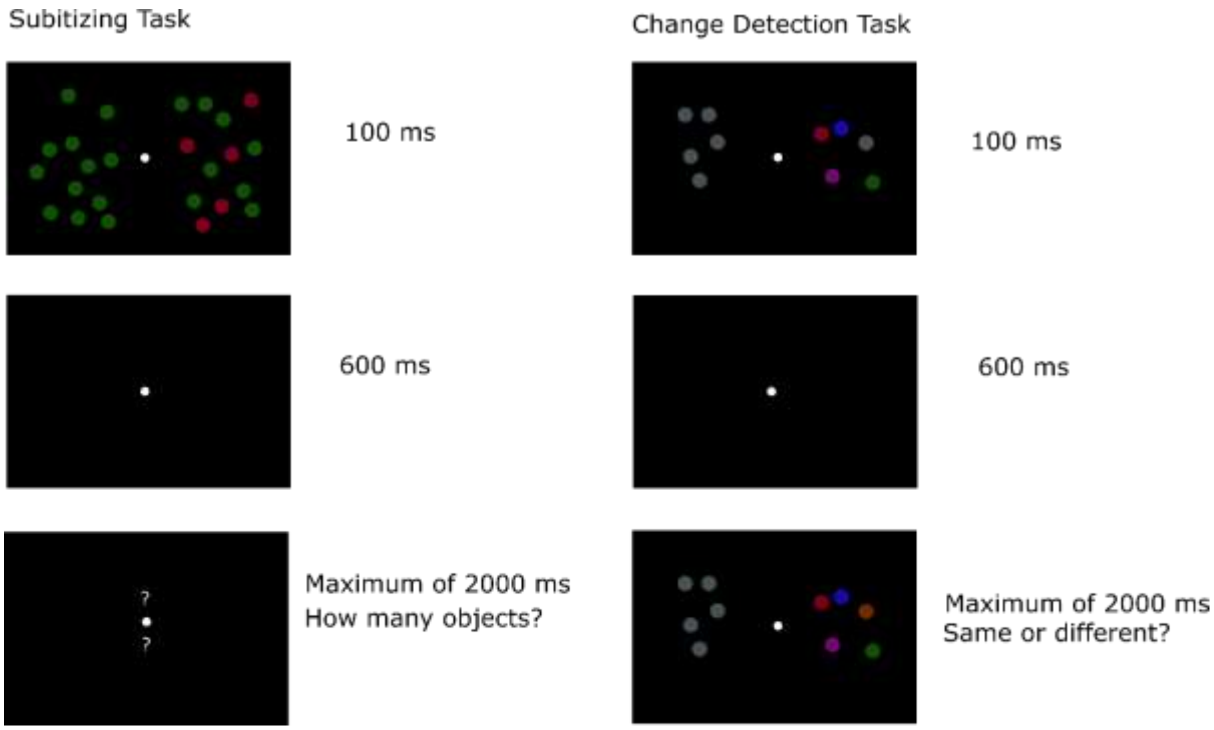


Figure 15. Depiction of an example trials from the change detection task and the subitizing task. The subitizing task show a numerosity of 5 red targets. The trial example of the change detection task is a high load condition with 5 target dots presented where participants memorise the colour in the target array and maintain the information for 600ms and then report whether there was a change in the colours or not.

Automated Operation Span Task. The automated Operation Span (OSPAN, Unsworth et al., 2005) is a computerized version of the OSPAN task (Turner & Engle, 1989) that estimates working memory capacity (scores between 0 and 75). The task was used to provide an external measure of general working memory capacity and attentional executive control. The automated OSPAN task has good validity (alpha = .78) and test-retest- reliability (r=.83, Turner & Engle, 1989)). The task involves completing simple math equations and memorising digits. Each trial begins with a math equation (e.g. (8/2)-1= ?) on the screen. Subsequently, participants were prompted with a number and had to indicate whether the number was the correct solution to the equation by pressing a “true” or “false” button on the screen. Participants have between 1-2 seconds to respond to the solution, the interval duration is determined by the performance in the practice trials. After each math equation, a letter was flashed up that they need to memorise. Each trial contained between three to seven math equations/letter spans. At the end of each trial a grid appeared and participants indicated the letter span by pressing the order of the letters on the grid. The task takes approximately 20 minutes to complete.

The automated OSPAN task, started with a practice block in which the participants familiarised themselves with a letter span task and solved simple maths problems separately and as a dual task. Across three experimental blocks, participants complete 72 trials of the dual task that comprised of the combined math/letter task.

Participants were matched in age, and IQ, and OSPAN performance.

Procedure

Ethics approval was received by the UCL Institute of Education ethics approval for postgraduate research students. Participants attended the EEG testing facilities for 1-1 testing sessions at UCL Institute of Education. Before the testing session participants received a detailed guide that explained the procedure of the study in written text, and pictures of the facilities and procedure. When participants arrived, they were shown the testing facilities and explained the procedure. After participants gave informed, written consent to participate, participants completed the various background measures (details in section above). Subsequently, participants were seated in an electronically shielded room and the EEG system was set up. The light was switched of for the duration of the EEG recording. Participants then completed two experimental tasks (see details in section below), the order of the task was counterbalanced between participants to avoid fatigue influencing the results. Participants were encouraged to take breaks in between the blocks and the experimenter checked on the participants frequently. After the two experimental tasks were completed, participants washed their hair and took a break. Subsequently, the WASI-II, FSIQ-2 was administered and participants completed the OSPAN task. Lastly, the autistic participants completed an ADOS. For three participants the ADOS was moved to a different session and ADOS data for three participants was already on record and therefore not repeated. The study took between 3.5 and 4 hours and participants were reimbursed £8 per hour and travel expenses.

Statistical analysis of Behavioural Data. In the experimental tasks, reaction time, accuracy, error rate, hit rate, false alarm rate and correct rejections were recorded and calculated. To assess performance on the change detection task, capacity scores (K, Pashler, 1988) were calculated using the following formula K= S((H-FA)/(1-FA)). Where S is the number of items in the set size, H the proportion of correct detections (Hit rate) and FA the proportion of false alarms (based on recommendations for change detection tasks with the full set size at presented as the test array (i.e. whole-display recognition; Rouder, Morey, Morey, & Cowan, 2011). Mean accuracy and reaction times were calculated for the different conditions for each participant. For the change detection task, repeated measure Analysis of Variances (ANOVAs) with group as between subject factor and load as within subject factor were performed on accuracy, reaction time and K score data. For the subitizing task, error rates and reaction time data were entered into separate repeated measures ANOVAs and group as a between subject factor.

EEG data recording

EEG data acquisition and Pre-processing of the EEG Data. Neural data were recorded through the BioSemi ActiveTwo system (BioSemi Amsterdam, The Netherlands) using the extended international 10/20 placement of the 64 electrodes in conjunction with the software Biosemi ActiView (Cortech-Solutions). The data were recorded at a sampling rate of 1024Hz. Additional external electrodes were used to record electro ocular activation. Horizontal eye movements (HEOG) were recorded placing electrodes at the outer canthi of left and right eyes. The sampling rate was down sampled to 512 Hz with a bandpass filter of 0.01-30Hz (Offline Butterworth zero filter). The data were offline re-referenced to the left and right mastoids. Experimental trials were stimulus locked into 800ms epochs from 100 ms before the onset of the memory/subitizing array and continued for 700ms. Artefacts in HEOG channels were rejected at 50mV and vertical electrooculogram (VEOG) at 60mV and all electrodes were analysed for myogenic artefacts at ±80 µV with a 200ms/0.5mV gradient relative to the 100ms pre-stimulus baseline.

On average 60% of the epochs were kept for the autistic participants in the change detection task and 66 % in the subitizing task. For the control group 52 % of the epochs were kept in the change detection task and 57% in the subitizing task.

Event Related Potentials Contralateral Delay Activity and N2pc. The N2pc and CDA utilise the contralateral organisation of the visual system. Contralateral and ipsilateral waveforms were calculated relative to the visual hemifield where target objects were presented. The difference between these waveforms (i.e., contralateral minus ipsilateral) produced N2pc and CDA difference waveforms, which were utilised for amplitude analysis. Analysis was based on N2pc/CDA difference waves obtained at posterior electrode sites PO7/PO8. Peak amplitude analysis was conducted 200-300 ms post-stimulus onset within the subitizing task to measure the N2pc component, consistent with analysis in previous studies (Ester et al., 2012). Mean amplitude analysis was conducted 400-700 ms post-stimulus onset within the change detection task to measure the more sustained CDA component.

For the change detection task, the mean amplitude for the CDA was entered as dependent variables into separate 2-way repeated measures ANOVAs with condition as a within-subject factor (4 levels: for each set size; 2,3, 4, 5) and group as between-subject factor (2 levels: autistic and non-autistic adults). In the subitizing task, the mean N2pc and CDA were entered into separate 2-way ANOVAs with condition as a within subject factor (5 levels: numerosity: 2,3,4,5,6) and group as a between subject factor (2 levels: autistic and non-autistic adults). Greenhouse-Geisser adjustments were made when sphericity assumptions were violated. Post hoc analysis were carried out using Helmert contrasts.

Results

Co-occurring conditions.

To test whether the groups differed on anxiety, depression, stress or ADHD symptoms, independent sample t-tests were performed (see Table 6.). Autistic people showed elevated symptoms for each of the conditions.

Table 6. Descriptive statistics for the self-report measures STAI-T, DASS-21, ASRS by group

	Non-autistic (*n* =18) *M* (SD)	Autistic (*n* =15) *M* (SD)	
Self-report measures	Range	Range	*p*-value
STAI-T	32.67 (8.46) 21 - 58	57.8 (20.46) 39 - 71	**<.001*****
DASS -21 Total Score	13.89 (11.41) 0 - 36	44.67 (30.37) 8 – 122	**<.001*****
SPQ	56.44 (14.96) 32-88	42.33 (20.44) 13-88	.029*
ASRS	7.24 (3.13) 0 - 13	13.05 (2.82) 9 – 20	**<.001*****

*Note. ***p<.001, *p<.05, STAI-T (State-Trait Anxiety Inventory, Trait Scale; Spielberger et al., 1983), DASS-21 (Depression Anxiety, Stress Scales -21, (Brown et al., 1997)), SPQ (Sensory Perception Quotient, Tavassoli, Hoekstra, & Baron-Cohen, 2014); ASRS (Adult ADHD self-report screener (Ustun et al., 2017))*

Change detection task

Behavioural Data.

Pashler K and reaction time measures were entered into separate repeated measures ANOVAs, with the factors Group (2 levels: autistic and non-autistic participants) and Load (4 levels: sets size 2, 3, 4, 5). The main effect of Load on K ($F(1.82,56.53)=37.01$, $p<.001$, $\eta p^2 = .55$) was significant, with increasing K with set size (see Figure 16). The main effect of Group and the interaction were not significant (*F*s<1). The main effect of Load on RT was also significant ($F(1.78, 55.32)=20.34$, $p<.001$, $\eta p^2 = .4$) as response times increased with increased numerosity. The main effect of Group, and the interaction were not significant (*F*s<1).

CDA.

Figure 17 shows the difference waveforms for the change detection task separately for both groups. Inspection of the difference waves show that the CDA was elicited at approximately 400ms and sustained for the duration of the retention period (up to 700ms). The main effect of Load on CDA amplitude was not significant (*F*(3,93)=1.03, *p*=.38, ηp²=.03). The main effect of Group (*F*(1,31)=1.24, *p*=.28, ηp² =.04) and the interaction (*F*<1) were not significant. Therefore, the groups did not significantly differ on behavioural or neural data in the change detection task.

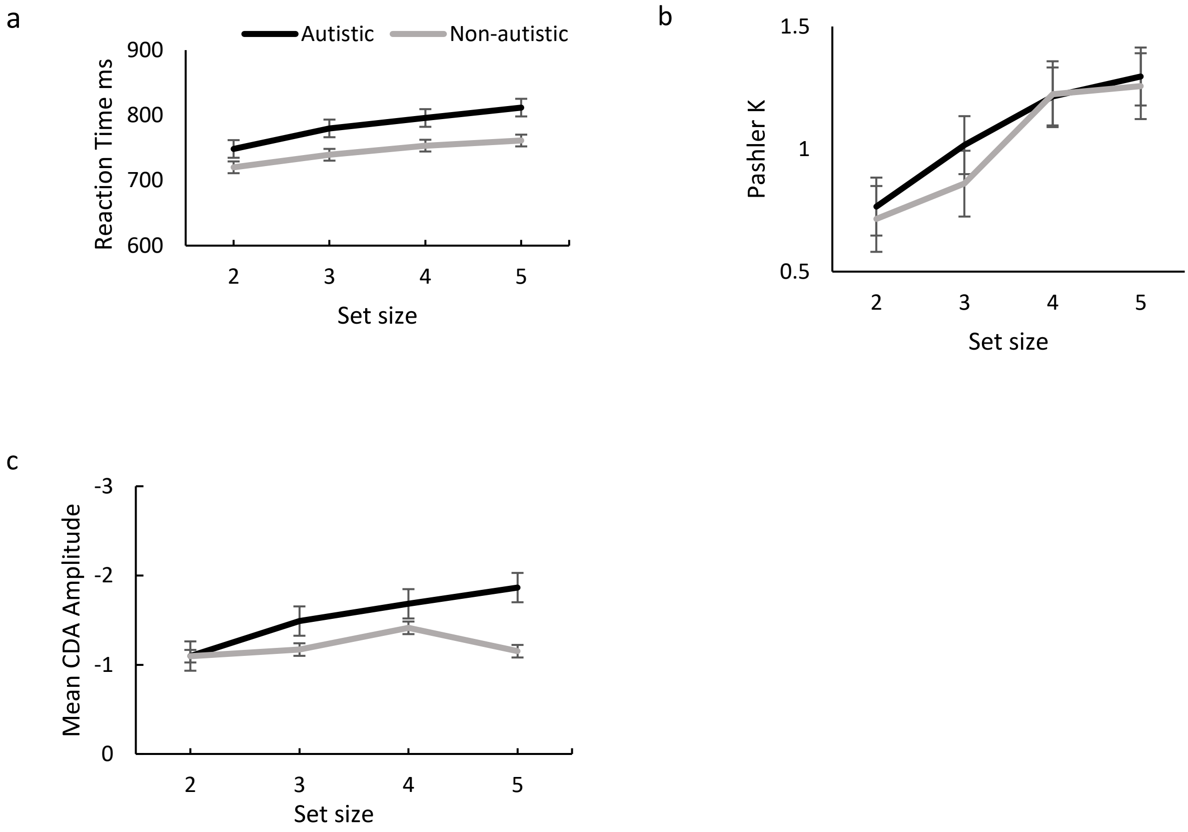
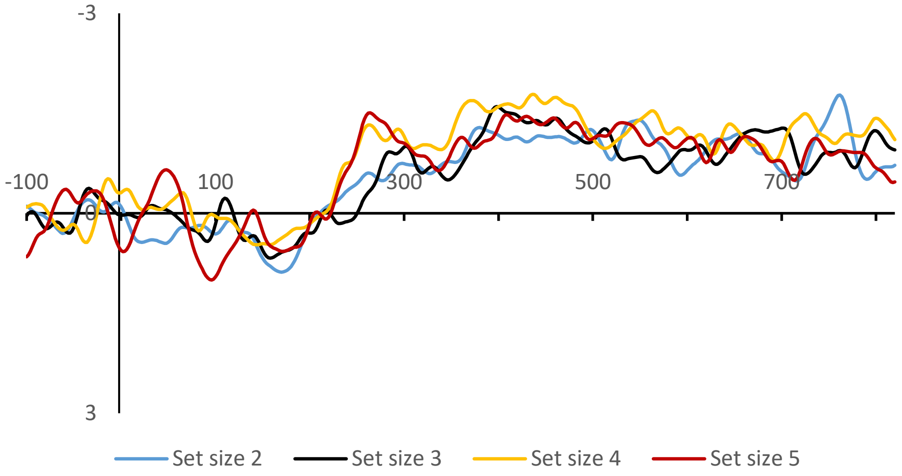


Figure 16. a) reaction time, b) Mean Pashler K, and) CDA amplitude as a function of set size for the autistic and non-autistic participants.

a



b

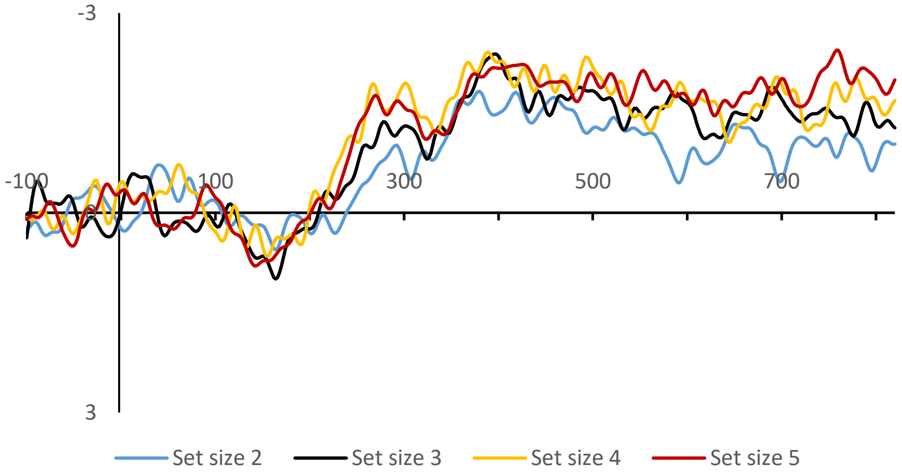


Figure 17. a) Difference waveform for non-autistic participants and b) the autistic participants for the change detection task computed by subtracting ipsilateral from contralateral waveform at electrode PO7/PO8 for set size 2-5.

Subitizing task

Behavioural data. Error rates and reaction times were entered into separate ANOVA with Load (5 levels: set size 2 -6) and Group (autistic and non-autistic participants) as factors (see Figure 18). The main effect of Load on error rates was significant, ($F(1.82, 56.45) = 31.71$, $p < .001$, $\eta p^2 = 0.51$), as expected and in line with previous subitizing studies the error rates increased from set size 2 to set size 6 (see Figure 18 for more details). Neither the main effect of Group nor the interaction were significant (*F*s<1). The main effect of Load on reaction time was significant (*F*(1.59, 49.2)= 9.8, p<.001, ηp^2=.24), with slower reaction times with increasing set sizes. The main effect of Group (*F*<1) and the interaction (*F*(1.59, 49.27)= 1.53, *p*= .23, ηp^2= .05) were not significant.

N2pc. Inspection of the difference waveforms Figure 19 shows that the N2pc was elicited around 200-300ms post stimulus onset and shows that the peak was more pronounced in the non-autistic participants compared to the autistic participants. This was confirmed with a significant interaction between Load and Group (F(4,124)=2.62, p=.038, ηp^2= .08). The main effect of Load on the N2pc amplitude (*F*(4,31)= 1.52, *p*=.20, ηp^2 = .05) and main effect of Group (*F*<1) were insignificant. Post hoc analysis using Helmert contrasts were conducted to follow up the significant interaction. In the group with non-autistic adults, the first contrast for the mean N2pc amplitude was significantly lower for the array with 2 items compared to higher numerosities (*t*(17)= 2.69, *p*=.009), but not when comparing set size 3 with higher numerosities (*t*(17)= 0.85, *p* =.398). This suggests that for the non-autistic adults the mean N2pc asymptote was reached at approximately set size 3. For the autistic adults, when comparing the mean N2pc amplitudes for the lowest numerosity with the mean amplitude for higher numerosities the effect was not significant (*t*(14)= .59, *p*=.56). This suggest that the asymptote was already reached at set size 2 for the autistic participants.

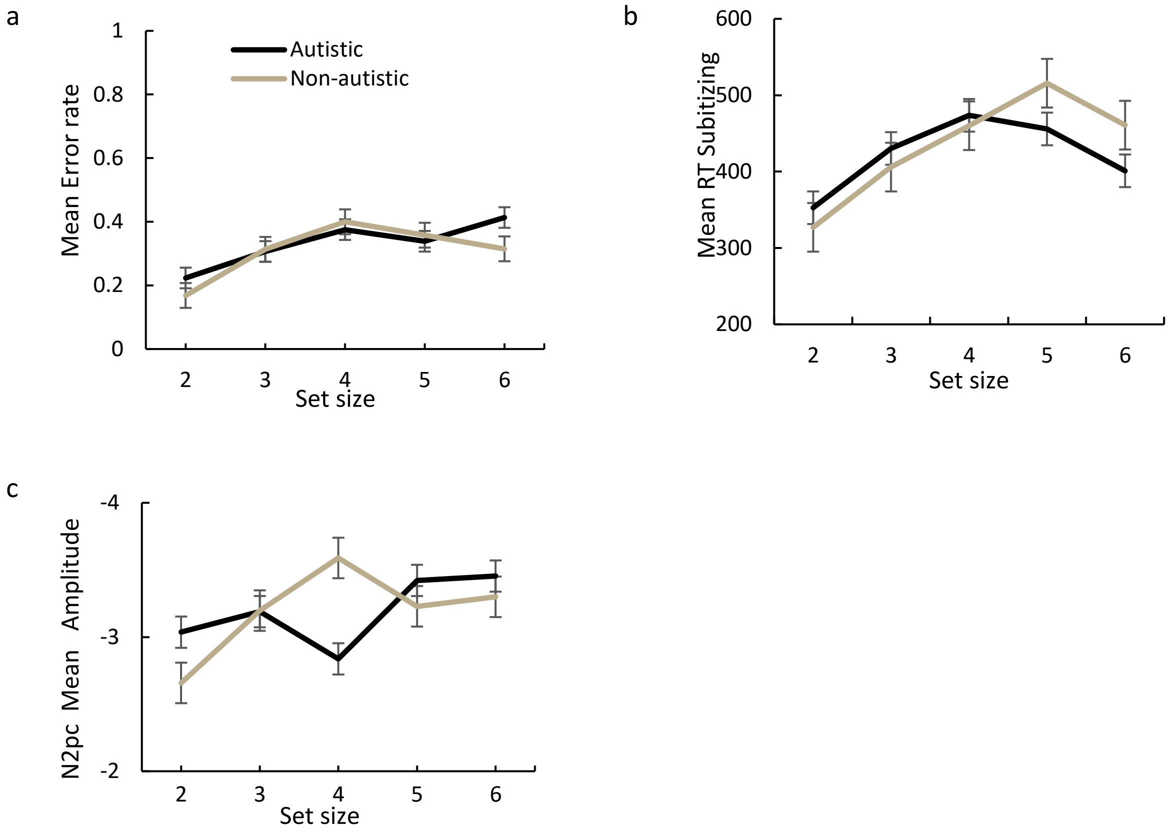


Figure 18. a) Error rate, Reaction Time (RT), b) Mean CDA 400-600ms interval, c) N2pc Mean Peak Amplitude plotted as a function of numerosity/ set size.

SPCN. The SPCN is believed to reflect post-selective encoding of information into visual working memory for subsequent analysis (analogous to the CDA component observed in tasks that require active maintenance of information in visual memory). Similar to the N2pc, the SPCN has also been suggested to be modulated by numerosity within the subitizing task (e.g. Pagano et al., 2014). Given the relevance of this to our research question, we additionally analysed the SPCN. Inspection of Figure 19. Difference waveform for the subitizing task for the non-autistic participants (top) and the autistic participants (bottom) at electrodes PO7/PO8 calculated by subtracting the ipsilateral from contralateral ERP for numerosity 2-6. Figure 19 shows a sustained SPCN wave following the N2pc component across an interval for the mean amplitude from 400-500ms post-stimulus onset. An additional analysis within this time window showed no significant main effects or interactions (*F*s<1). This indicates that there was no significant difference between numerosity or group during the post-selective phase within the experiment.

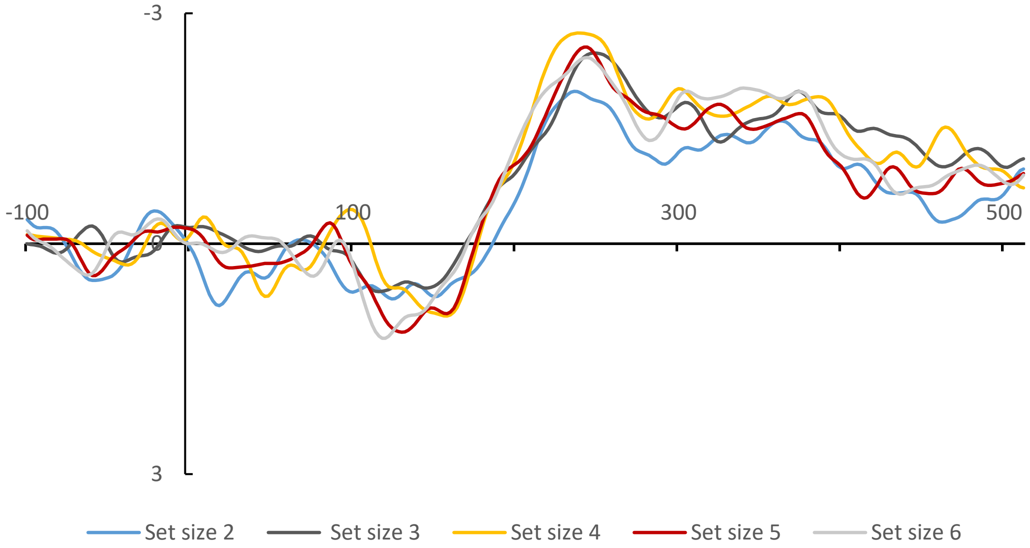


Figure 19. Difference waveform for the subitizing task for the non-autistic participants (top) and the autistic participants (bottom) at electrodes PO7/PO8 calculated by subtracting the ipsilateral from contralateral ERP for numerosity 2-6.

Additional Correlational Analysis

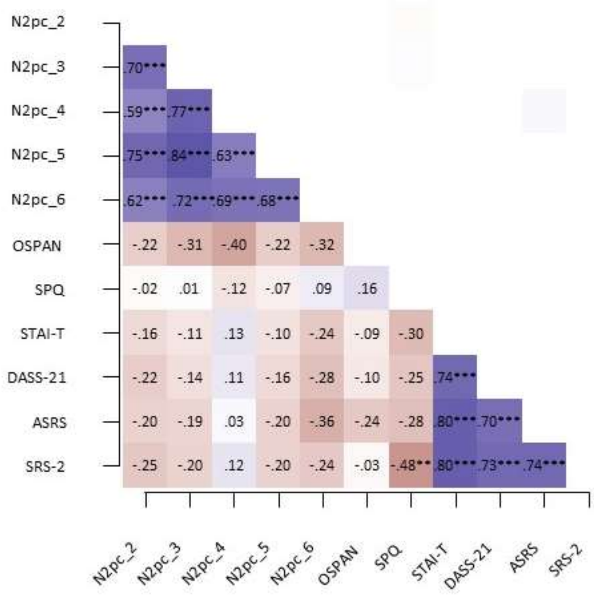
To determine possible confounding factors such as anxiety, depression, stress, ADHD traits and OSPAN on the N2pc amplitudes, correlations were conducted. Spearman's rho was used as the data were non-parametric. The N2pc amplitudes were positively inter-correlated across all 5 set sizes (see Figure 20 for correlation coefficients). In addition, the DASS-21, STAI, SRS and ASRS were positively correlated with each other. Corrections of the significance value of .05 for multiple comparisons using Bonferroni corrections ($\alpha_{adjusted}$= .005), indicate that the OSPAN and N2pc at set size 4 (p=.03) and set size 6 and ASRS scores (p=.04) and SPQ and ASRS do not survive the correction (p=.007; see Table 7). Therefore, there were no significant correlations between mental health scores, autistic traits, sensory processing, working memory span, ADHD traits and the N2pc amplitude with numerosities ranging from 2-6 items.

Table 7. Correlation matrix with N2pc components from set sizes 2-6, OSPAN, self-reprt mental health scores

Variable	Statistics	N2pc_2	N2pc_3	N2pc_4	N2pc_5	N2pc_6	OSPAN	SPQ	STAI-T	DASS-21	ASRS	SRS-2
1. N2pc_2	Spearman's rho	—										
	p-value	—										
2. N2pc_3	Spearman's rho	0.70	—									
	p-value	< .001	—									
3. N2pc_4	Spearman's rho	0.59	0.77	—								
	p-value	< .001	< .001	—								
4. N2pc_5	Spearman's rho	0.74	0.84	0.63	—							
	p-value	< .001	< .001	< .001	—							
5. N2pc_6	Spearman's rho	0.62	0.72	0.69	0.68	—						
	p-value	< .001	< .001	< .001	< .001	—						
6. OSPAN	Spearman's rho	-0.22	-0.31	-0.40	-0.22	-0.31	—					
	p-value	0.25	0.09	0.03	0.24	0.09	—					
7. SPQ	Spearman's rho	-0.01	< .001	-0.12	-0.07	0.09	0.16	—				
	p-value	0.94	0.96	0.50	0.70	0.62	0.41	—				
8. STAI-T	Spearman's rho	-0.16	-0.11	0.13	-0.12	-0.24	-0.09	-0.30	—			
	p-value	0.37	0.53	0.49	0.49	0.18	0.65	0.09	—			
9. DASS-21	Spearman's rho	-0.22	-0.14	0.11	-0.16	-0.28	-0.10	-0.25	0.74	—		
	p-value	0.22	0.43	0.55	0.37	0.11	0.59	0.16	< .001	—		
10. ASRS	Spearman's rho	-0.20	-0.19	0.03	-0.20	-0.36	-0.24	-0.28	0.80	0.70	—	
	p-value	0.27	0.29	0.85	0.27	0.04	0.19	0.11	< .001	< .001	—	
11. SRS-2	Spearman's rho	-0.25	-0.19	0.12	-0.20	-0.24	-0.03	-0.48	0.80	0.73	0.74	—
	p-value	0.16	0.28	0.50	0.27	0.18	0.87	< .001	< .001	< .001	< .001	—

Note. Bonferroni correction (αadjusted= .005), STAI-T (State-Trait Anxiety Inventory, Trait Scale; *Spielberger et al., 1983)*, DASS-21 (Depression Anxiety, Stress Scales -21, *Brown et al., 1997)*, ASRS (Adult ADHD self-report screener Ustun et al., 2017), SRS-(*social responsiveness scale, Constantino & Gruber, 2012)* OSPAN *(automated Operation Span, Unsworth et al., 2005), N2pc2, N2pc3, N2pc_4, N2pc_5, N2pc_6 indicate the N2pc amplitude at set size 2-6.*

Figure 20. Heatmap for Spearman correlations



	N2pc_2	N2pc_3	N2pc_4	N2pc_5	N2pc_6	OSPAN	SPQ	STAI-T	DASS-21	ASRS	SRS-2
N2pc_2											
N2pc_3	.70***										
N2pc_4	.59***	.77***									
N2pc_5	.75***	.84***	.63***								
N2pc_6	.62***	.72***	.69***	.68***							
OSPAN	-.22	-.31	-.40	-.22	-.32						
SPQ	-.02	.01	-.12	-.07	.09	.16					
STAI-T	-.16	-.11	.13	-.10	-.24	-.09	-.30				
DASS-21	-.22	-.14	.11	-.16	-.28	-.10	-.25	.74***			
ASRS	-.20	-.19	.03	-.20	-.36	-.24	-.28	.80***	.70***		
SRS-2	-.25	-.20	.12	-.20	-.24	-.03	-.48**	.80***	.73***	.74***	

Note. Bonferroni correction (αadjusted= .005), STAI-T (State-Trait Anxiety Inventory, Trait Scale; *Spielberger et al., 1983)*, DASS-21 (Depression Anxiety, Stress Scales -21, *Brown et al., 1997)*, ASRS (Adult ADHD self-report screener Ustun et al., 2017), SRS-(*social responsiveness scale, Constantino & Gruber, 2012)* OSPAN *(automated Operation Span, Unsworth et al., 2005), N2pc2, N2pc3, N2pc_4, N2pc_5, N2pc_6 indicate the N2pc amplitude at set size 2-6.*

Discussion

The present study directly compared differences in perceptual and visual working memory capacity in autism. Previous research has suggested that autism may be associated with enhanced perceptual capacity, and chapter 3 of this thesis also provided preliminary ERP evidence of similarly enhanced visual working memory capacity. Using two similar task procedures, one requiring enumeration of varying numbers of objects (subitizing task) and the other requiring visual maintenance of objects (change detection task), both behavioural and electrophysiological markers associated with individual differences in these different capacities were measured. Overall, I found no behavioural evidence of differences between autistic and non-autistic adults within either the subitizing or change detection tasks. When examining ERP markers, the mean amplitude of the CDA component within the change detection task showed equivalent performance for both groups. For both groups, the CDA appeared to reach an asymptote at set size 2, which corresponded to average behavioural K-value estimates of memory capacity ranging from .75 to 1.28 across the different conditions. In contrast, group differences were observed within the subitizing task when examining the N2pc component as a marker of perceptual capacity. While the amplitude of the N2pc component increased in line with increasing set size of objects requiring enumeration, the N2pc reached asymptote for the autistic group at set size 2 whereas, for the non-autistic control group, asymptote was reached at set size 3. Overall, our results were contrary to the hypothesis that autism may result in increased perceptual and visual working memory capacity (reflected by superior performance on the subitizing task). In fact, the reduced performance on this task in the present study suggests a reduced perceptual capacity in autism, and no influence on visual working memory capacity (equivalent performance between the groups on the change detection task). The pattern of the N2pc results suggests that for autistic people the influence on perceptual capacity occurs through a reduction in capacity. Thus, the number of items that can be simultaneously selected within the environment is reduced for the autistic participants.

No Group Differences in Visual Working Memory Capacity

Within the change detection task, there was no evidence of changes in visual working memory capacity associated with autism, as measured both by K-value behavioural estimates of capacity and differences in amplitude on the CDA component. Although the findings are consistent with the preliminary findings from Chapter 3, the CDA results do not support the findings of an increased visual working memory in autism. Due to the COVID-19 pandemic, the data collection was cut short and the sample size could not be increased for the study. In addition, the effect sizes presented in Chapter 3 were small (η^2=.04) for the interaction between load an group, a power calculation (Faul et al., 2009) to find small effects (d=.1) with an alpha level of .05 would require a sample of 1289 participants, which is beyond the scope of this thesis. This might be the reason why no group differences were observed. However, the findings from Chapter 3 were also marginal and might not have been reliable and therefore were not replicated in the present chapter. Nevertheless, the ERP differences waves are qualitatively consistent with the findings from Chapter 3 (see difference wave Figure 17 and Figure 12). Thus, this might suggest that the findings from Chapter 3 are in fact accurate, yet the study presented in Chapter 4 might have been underpowered. Together, these results suggest that visual working memory ability is preserved in autism, even when directly contrasted with perceptual capacity. It is important to note in the current study that there was generally no main effect of load observed on CDA components across the two groups of participants. That is, the CDA component appeared to reach asymptote even at set size 2 for both groups. While visual working memory capacity is usually estimated to be between three to four items (Cowan, 2010), and directly corresponds with amplitude differences on the CDA component (e.g. Vogel & Machizawa, 2004), this result is not unusual as other studies have observed overall lower visual memory capacities among both neurotypical (Sander et al., 2011) and clinical samples (e.g. Coffman et al., 2020). Results therefore suggest that a capacity of 2 items was the limit for both groups, with no evidence to support a reduction or enhancement to capacity among autistic participants.

A Reduced Subitizing Capacity in Autism?

The finding that autism was associated with a reduction in subitizing capacity, as measured by the N2pc component, contrasts with previous demonstrations that autism can be associated with improved perceptual processing, such as more efficient visual search (O'Riordan et al., 2001) and enhanced visual detection under increasing perceptual demands or load (Remington et al., 2009; 2012). However, the result is consistent with some behavioural studies that have specifically examined the role of autism in subitizing ability, with the finding of reduced capacity across childhood, adolescence, and adulthood (O'Hearn et al., 2013). That said, this effect may be influenced by differences in strategy, as previous studies typically include long exposure durations and do not mask visual items post-presentation, and so do not preclude the possibility of differences in overt counting of stimuli (O'Hearn et al., 2016). In the current study, this may explain why no behavioural differences in subitizing performance were evident between groups. However, the temporal precision of the N2pc component provides a more direct snapshot of initial attentional allocation and individuation of target items. The current study thus provides direct electrophysiological evidence for a potential reduction in subitizing capacity in autism.

How can this result be reconciled with previous evidence of enhanced perceptual capacity in autism, especially considering that the subitizing paradigm has been proposed to be a highly reliable marker of perceptual capacity which directly correlates with ability in other perceptual tasks such as multiple object tracking (Eayrs & Lavie, 2018)? One possibility relates to past evidence of heightened distractibility in autism (Adams & Jarrold, 2012; Lindor et al., 2019; Milne et al., 2013; J. W. Murphy et al., 2014b). Because of this, participants in the autism group may have been more likely to process additional task-irrelevant stimuli during visual presentations, filling their perceptual capacity even under the target set size 2 condition. Indirect support for this possibility can be observed within Figure 17 and the ERP data related to the change detection task. While not directly hypothesised, as can be seen in Figure 17 for to-be-memorised objects in the time window of 200-300ms also elicited evidence of N2pc components prior to the CDA component. Interestingly, evidence of a set size effect on the N2pc is observable up to around set size 3, both for the autistic and neurotypical control groups. A notable difference in this task compared to the subitizing task was that no additional task-irrelevant objects were present within memory encode displays. This suggests that differences in subitizing capacity might be accounted for by differences in the ability to selectively attend and individuate target items in lieu of non-target objects in autism, rather than differences in the capacity to individuate objects per se. Future research controlling for this possibility within a subitizing-like task would provide more robust scrutiny into the role of autism in subitizing capacity.

An alternative possibility is that reduced subitizing capacity in autism may represent an exception versus other measures of perceptual capacity. However, a recent study provides fMRI evidence that subitizing, change detection and object tracking show similar underlying activation and the right Inferior Parietal Lobule is predictive for perceptual capacity differences across all three tasks (Eayrs & Lavie, 2019). Another explanation for the reduced subitizing capacity in autism might have been related to the colour discrimination used in the paradigms for the present study. Franklin and colleagues (2008) reported that autistic children show less sensitivity to colour discrimination when compared to a group of non-autistic children matched in age and IQ. The These findings were replicated in further studies (Franklin et al., 2010; Heaton et al., 2008), however other case studies (Ludlow et al., 2014) and anecdotal evidence (Franklin et al., 2008) suggest a preoccupation for colour discrimination in autism. Similarly, a study that modelled eye-tracking data of naturalistic scenes identified that autistic adults show a greater orientation towards colour and orientation rather than semantic information or object saliency (e.g. the size or density of objects) compared to non-autistic adults (Wang et al., 2015). Whilst colour perception might have impacted the chromatic discrimination abilities of the autistic participants in the sample on the subitizing task, similar findings would be expected on the change detection task that required more colour comparisons to be maintained and discriminated. Future studies should address this and test this using achromatic objects instead of coloured objects.

Importantly, there are separate stages of visual attention; the selection stage in which targets and non-targets are distinguished and the access stage that makes information accessible for the conscious engagement of visual information (for an overview see Berggren & Eimer, 2020). In addition to the stages of visual attention, the Boolean map theory proposes that visual attention is most efficient when all the features are the same (e.g. red targets in subitizing task), multiple targets can however be accessed simultaneously when the target defining features are the same but not when features are different (Huang & Pashler, 2007). Berggren and Eimer (2020) have tested this across multiple experiments by manipulating target properties. The N2pc and behavioural evidence indicated that multiple target properties impaired the access. In the present study, the N2pc in the subitizing task reflects the access stage which appears to follow the expected pattern of an increased N2pc with an increased set size and therefore efficient object individuation and suggests an increase with the set size (e.g. in line with Ester et al., 2012). In contrast, the reduced N2pc in the autism group may be the results of over selecting target and non-targets and not distinguishing during the selection stage between the objects with two different features (red and green objects). Therefore, it might be that when it comes to the conscious selection of the information during the access stage reflected in the N2pc, that the capacity limit is reached at set size 2 as the objects have not been sufficiently distinguished to allow for object individuation. This might suggest that the mechanism that autistic people in the sample distinguish between objects result in differences in perceptual capacity at the ERP level.

Dissociable Differences in Perceptual and Visual Working Memory Capacities

Interestingly, the present results suggest a dissociation in autistic people between perceptual and visual working memory capacity, where the electrophysiology of the former appears to be altered while the latter was not, despite qualitatively similar tasks being employed. While it has been theorised that perceptual and visual working memory capacity may reflect a common shared resource (e.g. Konstantinou & Lavie, 2013), the finding of a dissociation may suggest that the magnitude of autism's effects on capacity are larger in the perceptual domain. This suggests some caution in the theoretical emphasis of a shared capacity in perceptual attention and visual working memory, as these two constructs do not appear to be entirely overlapping in autism. Given the importance of visual processes in everyday tasks, the findings of the current study can provide insights into education and workplace experiences, and ultimately inform the creation of support for autistic individuals, based on how the environment could be altered to better suit an individual's visual working memory capacity and improve learning and sustained attention. This could mean when presenting information that is maintained, e.g. items of a meeting agenda or key points in a presentation or lecture are presented with three items. However, when needing to assess how many objects are in one place, e.g. items on a shelf in a supermarket autistic people may have a slightly lower capacity.

Overall, in the present chapter, I present ERP findings of a reduced subitizing capacity in autism. Although the findings do not fit previous behavioural findings of an increased perceptual capacity, the results of the subitizing task are in line with prior behavioural and fMRI studies that suggest reduced subitizing capacity and point towards an atypical subitizing strategy. Therefore, it might be that subitizing tasks provides an exception for perceptual capacity in autism, which will be further explored in chapter 6. However, the aim of this thesis is not to investigate whether subitizing is different to other perceptual tasks.

Yet, one area that has not been systematically explored is whether attention can be improved through training programmes or specific interventions. In Chapter 1, I outlined that there is increased levels of distractor processing in autism. Recent advancements in the cognitive training literature have shown that aspects of attention can be trained and have led to improvements on working memory and mental health outcomes. Yet, not much is known about the cognitive training literature in autism. Thus, more specifically in Chapter 5 I will explore whether an online neurofeedback intervention is feasible and whether aspects of attention and mental health improve as part of the training.

Chapter 5

Feasibility of a Neurofeedback Online Meditation Intervention in Autism

Attention and executive functions are vital for all aspects of life, Chapter 1 has highlighted atypical attention that is evident in selective and executive attention in the autism literature and indicates increased levels of distractibility in autism. Whilst, the underlying mechanism for modulated attention in for autistic people is currently not known, more recently, in the attention literature training studies have emerged with the aim to improve attentional and cognitive processes and might offer novel avenues for cognitive training for autistic people. In the general population, attention gains have been detailed in the literature as a target of cognitive interventions training through domain general training such as working memory or meditation. Specifically, meditation training, through practicing conscious attention to the present moment and breathing, has shown gains in aspects of executive attention in the past, even when self-directed through a smartphone application. The feasibility of meditation interventions and its potential therapeutic use improving aspects of attention are however largely unexplored in autism. Therefore, in Chapter 5, I will assess the feasibility of an online intervention using a self-guided smartphone meditation application and neurofeedback in a sample of autistic adults.

Meditation is rooted in Buddhist techniques of spiritual observations of the mind (McMahan & Braun, 2017). In recent years, mediation has become of increasing interest in western cultures, and evolved into a secular approach that includes different subtypes of meditation, mindfulness techniques and clinically orientated meditation and mindfulness based programmes (Bishop et al., 2006). Likewise, the definitions of meditation have changed as the original characterisations were abstract, difficult to operationalise and test in a research framework. While there is a great deal of inconsistency in the definitions (which can make it difficult to compare results across studies e.g. Davidson & Kaszniak, 2015), psychologicallyoriented definitions have been put forward and typically include two specific components: the conscious attentional process from moment to moment on internal and external experiences and the engaging in the non-judgemental way to accept the sensations, feelings and mental states (Bishop et al., 2006). During meditation practice, attention can be focused on specific aspects such as breathing, an object, sounds etc. To sustain focus throughout the meditation practice, attention needs to be monitored to avoid distraction from within the body e.g. mind wandering or by external environmental distractors. Given that meditation practice necessitates focused attentional processes it might not be surprising that studies have shown that meditation practice improves aspects attention (Lippelt et al., 2014; Lutz et al., 2008).

In particular, Lutz et al. (2008) proposed that four attentional processes are necessary for meditation practices; 1) sustained attention, 2) attention monitoring, 3) shifting attention back to meditation practice when distracted and 4) non-judgemental appraisal of the distractor. A recent meta-analysis explored this further through examining data from executive function tasks divided into the attentional subdomains of inhibition, shifting and updating of information, and whether these are related to meditation practice (Gallant, 2016). The review was based on 12 studies and showed that in non-clinical groups inhibitory functions are most likely to improve through mediation practice. Specifically, decreased reaction times were found across studies on tasks such as Stroop or Go-no-go tests as a results of meditation training. Less consistent evidence for improvement was found on tasks that tapped into shifting and update subdomains as dependent variables. Together these findings suggest that there is evidence for changes in attention and executive functions through meditation practice (Gallant, 2016).

In addition to the evidence of improved attention, a considerable body of evidence has detailed the benefits of a meditation programme on mental health in clinical populations (e.g. patients with depression and anxiety) and non-clinical populations, suggesting a reduction in negative affect and emotion regulation. In particular, a review by Goyal and colleagues (2014) compiled evidence of patient groups with psychiatric conditions (including anxiety and stress disorders) as well as physical health conditions (such as chronic back pain or heart disease), and suggested that there might be small to moderate reductions in psychological stress. However, there was no evidence of meditation being more effective than any other active treatment such as behavioural therapy or drug treatment (Goyal et al., 2014).

Given the potential benefits of meditation training in the general population, meditation might be a feasible intervention for autistic people and might offer novel therapeutic avenues. As outlined in Chapter 1, autistic people often present both atypical attention and mental health challenges. Therefore, the current study will investigate the feasibility of a meditation training in autism to see if it benefits attentional processes and mental health. Whilst studies have aimed to improve behavioural outcomes for autistic children such as aggression, others have aimed to improve social and empathic traits and some studies have investigated this through parental mindfulness training (for a review Sequeira & Ahmed, 2012). Similarly, in a systematic review with six studies that showed a reduction in rumination, anxiety, depression and increased positive affect through meditation based training in autistic children, adolescents and adults (Cachia et al., 2016). In a randomised control trial, Spek et al. (2013) indicated that a nine week mindfulness training adapted for autistic people improves depressive symptoms and reduces rumination compared to a waitlist in a sample with autistic adults (e.g. Spek et al., 2013). In a later study using the same meditation programme, Kiep and colleagues (2015) found that effects of improved mental health scores were sustained at a 3 months follow up. In a recent randomised control trial, Sizoo and Kuiper (2017) compared the effectiveness of a cognitive behavioural therapy programme and a mindfulness stress reduction programme with 59 autistic adults who had high levels of anxiety and depression. Both programmes were administered in group sessions and each lasted 13 weeks with 90 minute sessions a week. Participants in both groups showed a reduction in anxiety and depression directly after the programme and at a 3 months follow up. Instead of using a group based intervention, Gaigg and colleagues (2020) investigated meditation training using a self-help online intervention. In the study 54 autistic adults were randomised to either an online cognitive behavioural therapy, a meditation programme or were in the waitlist control group. Data on anxiety was measured at baseline, after the 6-8 week intervention and a follow up at 3 and 6 months after the intervention. The results indicated that either using an online self-guided cognitive behavioural therapy or meditation practice were effective in reducing anxiety in a randomised waitlist control trial in autistic adults, and these effects were sustained for 3 months post intervention. Whilst these findings consistently support evidence for a reduction in mental health symptoms for autistic people using online or group based meditation session, there is a paucity in studies investigating the impact of meditation on attention in autism.

Whilst meditation is the internal focus of an individual and therefore a solo endeavour, the guidance through the meditation practices is often delivered by an expert in a 1:1 setting or as a group setting. As this might be challenging for autistic people, given that social anxiety is high in the condition (e.g. Maddox & White, 2015), a meditation practice in a social setting might be less conducive for those autistic people with high social anxiety. It is therefore not surprising that autistic people have indicated that testing the feasibility of self-managed tools should be a research priority in the autism literature (Benevides et al., 2020). Especially in the meditation literature in autism, previous work has excluded autistic adults who were unable to participate in group meditation settings as part of the study (Sizoo & Kuiper, 2017). In recent years smartphone and online intervention have become more popular and may offer some novel solutions. As such, the randomised control trial by Gaigg and colleagues (2020) used an online self-guided meditation practice in a trial with autistic adults. Whilst the study found that anxiety was reduced through the online self-guided programme, the qualitative experiences and the feasibility for the autistic people was not systematically analysed in the study, due to a reduced number of responses in an experience diary. Therefore, while smartphone and online interventions might enhance the meditation experience and outcomes for autistic people compared to traditional meditation interventions, the experiences and feasibility have not yet been studied systematically. Novel self-guided meditation approached have emerged in recent years utilizing the neural underpinnings of meditation (e.g. neurofeedback). Alpha and theta synchronisations have been proposed to be linked to attention processes that are internally directed, such as required during meditation practice (Lee et al., 2018). Systematic reviews have supported these finding suggesting that mindfulness is associated with increased levels of alpha and theta synchronisation that has also been suggested to be advantageous for mental health (Lomas et al., 2015). In particular, it has been proposed that using EEG techniques, changes in brain waves that are linked to increased alpha and theta waves and can be detected and might serve as an objective marker for meditative states (e.g. Rodriguez-Larios et al., 2020) and help to identify whether someone is effectively meditating through guidance of audio or visual feedback. Therefore, these biomarkers offer neurofeedback mechanisms that may help to guide the meditation practice. It is currently unclear whether an intervention for autistic participants using neurofeedback- guided meditation is feasible.

In the present study, I employed the neurofeedback mechanism of the Muse headband (InteraXon Inc., Toronto, Canada), which is a commercially available neurofeedback device with integrated EEG dry sensors. The Muse headband detects the brain activation through the EEG sensors based on oscillatory patterns (e.g. alpha and theta activation). The headbands connects to a smartphone application and has an integrated algorithm that translates the neural activation into a soundscape based on the meditative states (e.g. gentle rain and birds tweeting for calm states and heavier rain represents distraction and mind wandering). The aim of the auditory feedback is to improve meta-cognition and awareness to distraction and attention lapses through the auditory cues. When using the headband to translate the EEG synchronisation into auditory feedback to allow the person meditating to direct the attention to the auditory sounds and recognise distraction immediately. The device has recently been compared to a research grade headband and was found to show that the N200 and P300 and related peaks were detectable using the Muse headband when the electrode positions of the standard montage were matched to the Muse headband (Krigolson et al., 2017). Preliminary evidence suggests that in a small sample (n=26) in a randomised active control trial over 6 weeks with 10 minutes a day, participants using the headband showed reduced reaction times on a Stroop task and improved self-reported executive functioning compared to a group that completed a math training (Bhayee et al., 2016). Similarly, Crivelli et al. (2019) suggest that undergoing neurofeedback training using the Muse headband improved neural efficiency as measured on the N2 component within a Stroop task, as well as improved behavioural performance and increased resting state responsiveness post training compared to a group of participants that listened to qualitatively similar sounds as the auditory feedback in the Muse condition. A recent study emerged suggesting that both a Muse neurofeedback condition and an active control group meditating with a smartphone application showed reduced depression, anxiety and stress, and both groups reported high levels of satisfaction with the training intervention that they had received (Hunkin et al., 2020).

Given the potential benefits of these technological assisted meditation tools, it is necessary to test the feasibility and effectiveness of such tools in clinical groups such as autism. The feasibility and qualitative experiences of those taking part in such trials, however, remains unknown. Understanding the positive and negative aspects of the training procedure itself (rather than focussing solely on outcomes) is crucial to ascertain the feasibility of an intervention for widespread use within the autistic population. The present study aims to address this question by considering the feasibility and acceptability of a self-administered smartphone-guided mediation tools. Here, in a mixed methods study, I use an active control, longitudinal trial to test the feasibility and effectiveness of improving attention and mental health in autism. To the best of my knowledge this is the first study to test a neurofeedback meditation intervention in autism. Therefore, it is necessary to assess the feasibility of a neurofeedback intervention and whether the method is acceptable by the autism community as measured in compliance and self-report rates. In addition, the study aimed to assess whether technologically supported meditation practice by either an EEG headband or a smartphone application can help to 1) improve attentional performance on executive function tasks and 2) improve mental health.

Methods

Participants

The study was pre-registered through the open science framework (https://doi.org/10.17605/OSF.IO/5NCY2) and the aim was to recruit between 50-70 participants for the online training study, to ensure that sufficient research resources (e.g. headsets) were available. In addition, a priori power calculations were conducted, the statistical power for the study was sufficient to reach large effect sizes (*d*=.77-.63; Faul et al., 2009). The sample size was higher than in previous feasibility meditation trials (Zylowska et al., 2008, n=24).

A total of 227 participants registered their interest online for the online training study. They completed an eligibility self-assessment survey (see Appendices for more details) on Qualtrics (*Qualtrics*, n.d.) that was distributed to the social media and charities. The eligibility criteria for the study were:

1) A clinical diagnosis of autism;
2) Age 18 or over;
3) Daily access to a computer and smartphone with internet connection,
4) Willingness to participate in a 14-day mediation programme with involvement of 10 minutes a day and pre-, post and 4-week follow up assessment
5) Novices at meditating and no regularly engaged in meditation or mindfulness practice more than once a week over the past 3 years;
6) No sensory difficulties that could make wear something such as headphones difficult and;
7) Not to have a history of epilepsy to avoid potential interference with Muse headsets.

Of the 227 participants who completed the eligibility screening, 16 participants did not meet the inclusion criteria for the study (see CONSORT flow chart, Figure 21). Ninety-one participants clicked on the link but did not consent to participate. At the end of the eligibility assessment, participants were given the opportunity to give written informed consent to participate in the intervention study. Fifty-five participants were moved to a waiting list, as the study was advertised online and it exceeded the capacity of the project.[5]

After exclusions and withdrawals from the study, the final sample included 47 autistic participants (see procedure for more details). Participants were randomly assigned to the experimental (n=27) and active control (n=20) condition, when enrolling to participate in the study. Participants were recruited via advertisements through social media channels, branches of the National Autistic Society and the Autistica Discover network.

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[5] The COVID-19 pandemic forced the United Kingdom into lockdown in March 2020 and therefore additional participants from the waiting list could not be recruited to the study.

Table 8. Demographic information for the experimental and active control group

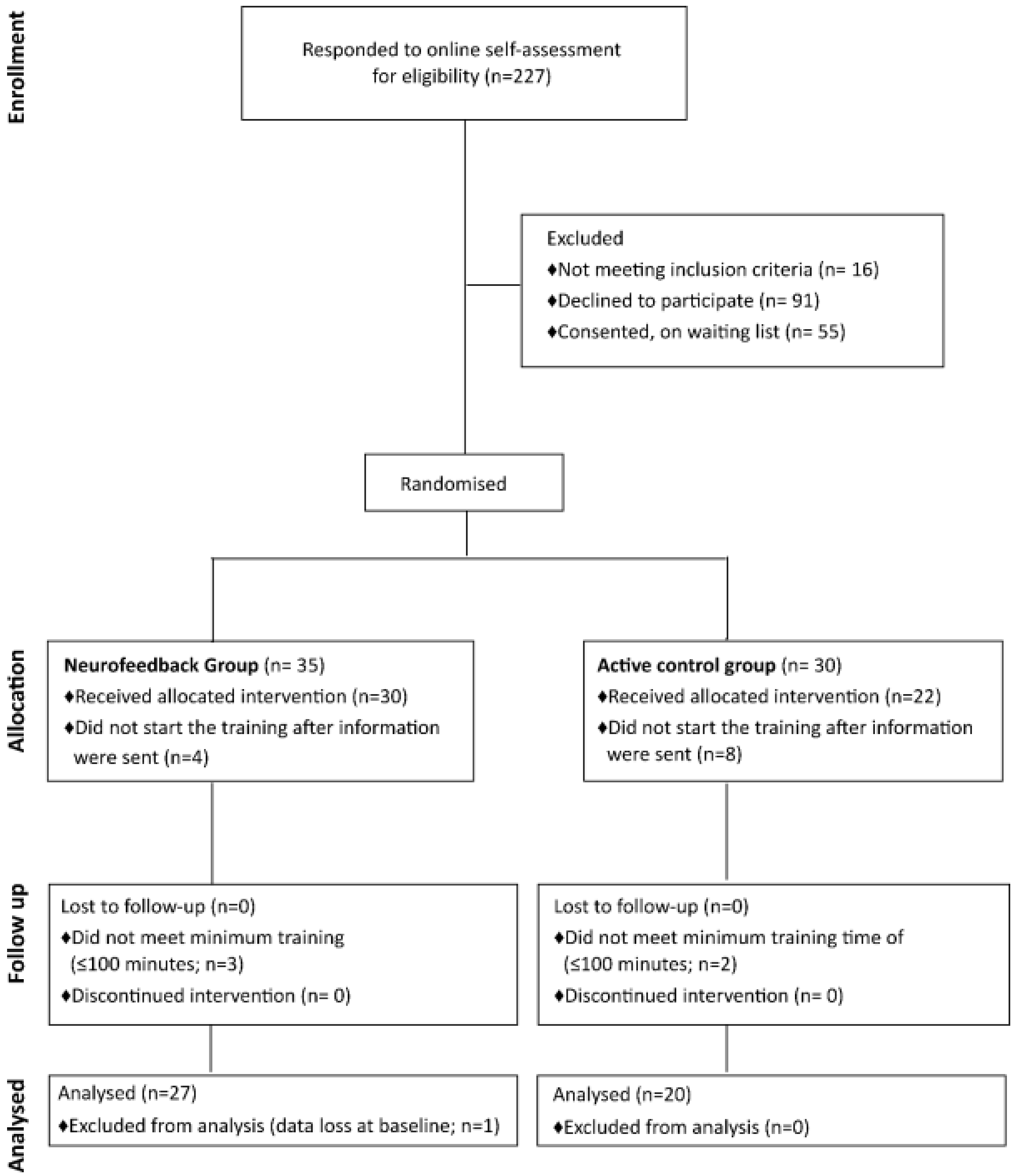
	Experimental condition (*n* =27)		Active control condition (*n* =20)		
Variables					
Gender identity; *n*, (%)					
Female (including trans women)	19	(70.3)	11	(55)	
Male (including trans men)	8	(29.6)	7	(35)	
Binary	0		2	(10)	
Prefer not to say	0		0		
Age (in years); *m, SD*	39	(14.35)	34.65	(9.46)	.25
Range	18 – 66		21 - 55		
Age of diagnosis in years; *m*, *SD*	31.18	(16.88)	20.16	13.05	.02*
Range	0.5-62		3-44		
Employment; *n*, (%)					
Fulltime	6	(22.2)	6	(30)	
Part-time	1	(3.7)	2	(10)	
Unpaid work	4	(14.8)	1	(5)	
Student	8	(29.6)	4	(20)	
Self-employed	3	(11.1)	2	(10)	
Other	3	(11.1)	5	(25)	
Missing	2	(7.4)	0	(0)	
Highest Education; *n* (%)					
GCSE	1	(3.7)	1	(5)	
A-level	4	(14.8)	4	(20)	
BTEC	0	(0)	1	(5)	
Bachelor	5	(18.5)	4	(20)	
Masters	8	(29.6)	6	(30)	
Doctoral Degree	0	(0)	0	(0)	
No formal degree	2	(7.4)	1	(5)	
Foundation degree	2	(7.4)	1	(5)	
Postgraduate Certificate/ Diploma	3	(11.1)	1	(5)	
Other	2	(7.4)	1	(5)	
Missing	0	(0)	0	(0)	
SRS-2 T scores; *m*, (*SD*)	77	(8.42)	77.75	(7.67)	.18
Range	67 – 90		60 - 89		
Co-occurring conditions (frequencies)					
ADHD	3	(11.1)	7	(35)	
Dyspraxia	2	(7.4)	1	(5)	
Dyslexia	4	(14.8)	3	(15)	
Learning Disorder	1	(3.7)	2	(10)	
Prefer not to say	0	(0)	1	(5)	

Note. GCSE=General Certificate of Secondary Education; BTEC=Business and Technology Education Council; SRS-2 (Social Responsiveness Scale; Constantino & Gruber, 2012)

All participants were aged between 18 and 66 years (see Table 8 for demographic information). All participants reported that they received a diagnosis from a clinician and participants also completed the self-report Social Responsiveness Scale 2 (SRS-2; Constantino & Gruber, 2012, see Measures for more detail) to ensure that participants scored above the clinical cut off for autism. All participants met the clinical threshold suggestive of autism which was a t-score of 60 and over. Participants reported additional diagnoses, most frequently for a) ADHD, b) mental health challenges, c) unique sensory sensitivity or processing, d) physical health challenges. Participants were matched on age, and executive outcome measures at baseline. Groups also did not differ in demographic information (Table 8), however, participants in the experimental group were significantly older when they received their autism diagnosis although the variance for age of diagnosis in both groups was high.

Procedure

Figure 21. Consort Flow-chart



Participants who signed up for the study on Qualtrics were issued a randomly generated ID number on Qualtrics that was sent to the participants via email with the study details. Random allocation was also achieved through Qualtrics by allocating the participants (1:1) to either the experimental or active control condition.

In order to be admitted to the training programme, participants had to complete the baseline measures within 7 days of signing up to the study. The link to the baseline measures was sent automatically to participants email address after participants gave informed consent to participate in the study.

After completing the baseline measures, the training information were sent to the participants. All participants in the neurofeedback condition were sent an email with detailed written instructions about the study and video links on how to operate the "Muse: meditation assistant" smartphone application that was used for the study.

In total the estimated study time was around 90 minutes for the pre- post and 4 week follow up assessment plus 100-140 minutes of meditation training and participants received a £10 shopping voucher for their time. Participants in the experimental condition were told at the end of the study that they could keep the Muse neurofeedback device. Ethics approval was received by the UCL Institute of Education ethics approval for postgraduate research students.

Meditation training

Once participants completed the baseline measures for the study, they received an email containing the information about the training details and how to proceed with the training. Written and video guidelines were created for the participants to ensure that they could follow each step of the installation guide that they needed to complete the training. In addition to the email instructions, the participants in the Muse meditation condition received a Muse meditation headset in the post, including a travel case, charging cables, printed written guides on how to install and use the meditation intervention. To deliver the meditation training, the smartphone application "Muse: meditation assistant" by Interaxon Inc. was used. The video and written instructions talked the participants through the installation procedure and set up of the application. Participants were issued a unique email address to allow for data protection and anonymity. The smartphone application allowed participants to personalise the soundscape from a set of options, set reminder options for a daily practice etc.

Figure 22. Depiction of Muse 2 meditation headband with its integrated sensors (top left) and the fit of the headband on the forehead (right side) and the Muse meditation assistant smartphone application (bottom left), image retrieved from https://images-na.ssl-images-amazon.com/images/I/51IJeZr6dOL._SS300_.jpg

Neurofeedback meditation device and Neurofeedback training (Headband Group)

Interaxon Inc.'s Muse meditation headbands Model MU-02 were used for the experimental condition. The headband is a wireless EEG headband that sits on the skin in the middle of the forehead of the participant and bends around the ears (like the temple and ear piece of spectacles). The headband has integrated dry EEG sensors, two for the mastoids and two that fit around the forehead (see Figure 22 for the fit of the device). The headband size is adjustable in size with extendable forehead straps. The device connects via Bluetooth to a dedicated smartphone application. A copyrighted Muse algorithm that is based on frequency bands associated with meditative states translates the neurofeedback into auditory feedback. The soundscapes that the participants can select gives feedback based on the levels of attention, such as stormy weather as a cue for distraction and calm weather sounds when attention is refocused on the meditation practice.

At the beginning of each meditation session the smartphone application talked the participants through a step-by-step instructions for the correct fit of the meditation headband. The connectivity of the headband is assessed at the beginning of each meditation session and participants are instructed to adjust and reposition the headband to improve signal quality as required. Once adequate signal was obtained, a short calibration began in which voice instructions through the smartphone application talk participants through the short recording of baseline data at rest. Before the meditation started a short-guided meditation, instruction was delivered and talked participants through e.g. attention to breathing. The instructions were slightly different each day and were aimed to help the participants improve the meditation experience. The neurofeedback from the Muse device was delivered through auditory signals. The soundscapes can be set by the participant individually depending on their preferences. The auditory signals involved e.g. weather sounds. If the participant's mind wandered, the signal changed to auditory cues that signalled e.g. stormy weather (depending on the selected sound scape) to indicate distraction. If participants are calm and in meditative states, the auditory signal indicates this with calm waves. At the end of the 10 minutes a sound alerted the participants that the meditation training was finished. The participants then saw a summary graph of their neurofeedback of the 10-minute meditation session.

Training in active control group

The Muse meditation application also has an option to set up a timed meditation in which the participants are presented with their preferred soundscape. The participants were made aware that the smartphone application can be used with an additional device, however, this was not used for this part of the study. When selecting the timer option, the neurofeedback device is not mentioned in the instructions and the participants complete the exact same guided meditation instructions as the participants in the neurofeedback condition (e.g. are instructed to pay attention to their breathing for the session). There was no calibration involved in the active control group as no headset was needed. Participants were encouraged to close their eyes and then started their 10 minute meditation intervention and random sounds of their selected soundscape were played. After 10 minutes a sound alerted the participants of the end of the meditation practice. A graph showed their weekly minutes of training at the end of the session.

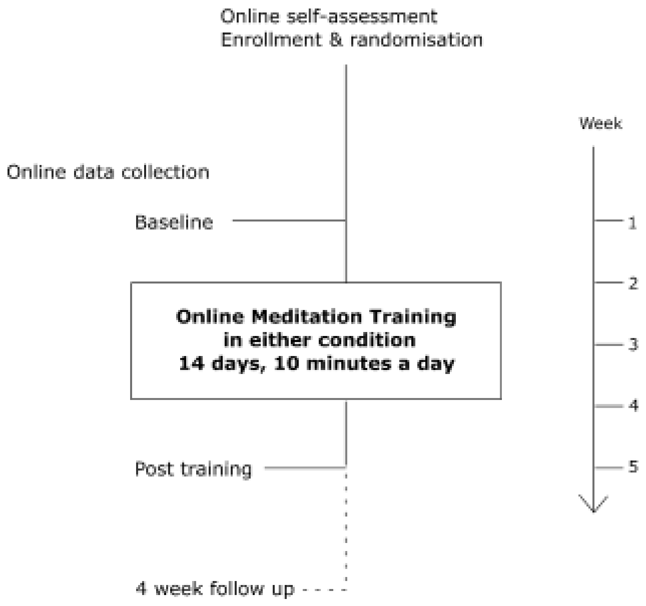
Tracking of daily training and adherence

Participants completed 10 minutes of training each day for 14 days. To ensure that participants were completing the training on a daily basis, a website (https://museconnect.choosemuse.com) from Interaxon inc. with researcher access was used to track the daily progress. The website showed the length of the mediation for each participant. Participants had to complete a minimum of 10 sessions with 10 minutes each to be considered to complete the training. If participants missed two consecutive days of training, the researcher emailed the participants to remind them of the training.

Time line of the intervention study

The data was collected between November 2019 and projected to finish in April 2020 (see Figure 23). The UK entered into a nationwide lockdown due to the Coronavirus Disease 2019 (COVID-19) on 23rd March 2020. The pandemic caused an unprecedented disruption to the people's daily life and led to a severe impact on mental health (R. G. White & Van Der Boor, 2020). In addition, a recent pre-print suggests that mental health impact is more negative for autistic compared to non-autistic adults (Oomen et al., 2020). Therefore, the 4-week follow up data was removed from the sample as for 23 participants the 4 week follow up time point coincided with the COVID-19 pandemic. This exclusion avoided any confounding effects on the data.

Figure 23. Time line of meditation study involvement in weeks.



Note. The enrolment was open between October 2019 – January 2020, the 4-week follow up data was taken out of the analysis as it coincided with the onset of the COVID-19 pandemic for some participants.

Adaptations for an autism friendly online intervention

To ensure that participants expectations of the training were met and uncertainty around the study was reduced, clear instructions were provided including; the length of the involvement in total and how long each task or questionnaire took to be completed. An extra page with a visual depictions of the duration of the training, and their daily involvement over the course of time was used. Participants had to specifically confirm that they had seen the page to show that they understood the involvement. In addition, participants were told that a smartphone application was used to guide the meditation practice and participants confirmed that they had a suitable smartphone with Bluetooth and internet to and were happy to install the application on their phone. In addition, videos were created for participants to show them how to install and use the smartphone application and set up the Muse meditation headband.

Measures

Background measures

Demographic information. During the first online self-report assessment, participants completed demographic background questionnaires on age, age of diagnosis, highest level of education and additional co-occurring conditions.

Social Responsiveness Scale (SRS-2). The SRS-2 which is a validated and reliable 65-item scale used to assess self-reported autism traits (Constantino & Gruber, 2012). On a 4-point Likert scale (0=not true to 3=almost always true), the categories of restricted interests and repetitive behaviour and social aspects of awareness, cognition and communications were assessed. The scale has excellent test-retest reliability (.88-.95) and an interrater reliability of (.61-.92) and good internal consistency (α=.95; Bruni, 2014). All participants scored above 60 which indicates moderate to severe classification of the impact on everyday social interaction consistent with the SRS scores of the clinical population (Constantino & Todd, 2003).

Executive function tasks

Participants completed the following executive function tasks, pre-, post-training and at 4 week follow up. The following tasks were created and administered on Gorilla.sc an experimental task builder platform. Visual representations of each task were used to present the instructions to the participants. All tasks were piloted and presented to a group of autistic participants to ensure that the instructions were clear and explicit. It took around 15 minutes to complete the tasks.

The order of the tasks was counterbalanced through Gorilla to avoid any effects of fatigue systematically affecting the results.

Corsi-Block Tapping task

An online block tapping task was used to assess executive functions. The Corsi-Block tapping task was originally designed by Corsi (1972) as a physical task in which the examiner tapped the blocks with a stick and the participants memorise the order. The task automated online version has become a standardised task to access updating in executive function and is a way to access visual working memory span.

Each trial began with a fixation cross that remain on the screen for 1000ms, subsequently nine black squares appeared on the screen. Participants were told that one after another, the blocks would flash up in yellow and that they had to memorise the order that the blocks changed colour. The blocks flashed up one by one for 700 ms and in between the stimuli was a 300 ms interstimulus interval where all blocks remained black, before the next block flashed up. Participants then selected the sequence in the order that they remembered. Once participants clicked on the square, it lit up in blue and stayed blue until the end of the trial. The difficulty for the task was adaptive, all participants started with the set size three (e.g. three blocks flashed in the sequence and the order had to be remembered), when they completed the task correctly, one block was added. If participants did not get the order right, the set size was reduced by one item. However, the lowest set size was three, if participants did not memorise the order of the three blocks correctly, they were presented with three blocks again. The highest possible number to memorise was nine blocks for the experiment. If they completed 9 blocks correctly, they started off with 3 blocks again. Participants received no direct feedback, but may have noticed that the set size increased or decreased depending on whether their responses were correct or incorrect.

Cued Task Switching

The cued task switching paradigm was used in the present study (see for original paradigm Jersild, 1927). Each trial began with a fixation cross, on the centre of the screen that was presented for 250ms. Subsequently, the word COLOUR or SHAPE appeared on the screen for 500ms and was replaced by one single object that appeared in the centre of the screen. The objects was either a circle or a square presented in either blue or green. Participants were given two sets of instructions depending on what word appeared on the screen. When the word COLOUR appeared on the screen at the beginning of the trial, participants had to respond to the colour of the object and ignore the shape of the object. When the object was green participants pressed the m-key on the keyboard and when the object was blue participants pressed z. However, when the word SHAPE appeared on the screen, participants had to ignore the colour of the object and respond to a circle by pressing m and to a square by pressing z on the keyboard. Participants were given visual cues on where to place their hands on the keyboard (i.e. m and z key). There was no time limit on how long participants could take to respond to the objects, however, participants were encouraged to respond as quickly and accurately as possible. Participants received feedback on their performance throughout the experiment. Participants completed 16 practice trials before the instructions were reiterated and participants completed the main experiment. The main experiment consisted of 3 blocks with 24 trials.

Flanker Task

The Flanker task (based on Eriksen & Eriksen, 1974) consisted of 108 trials and took around 5 minutes to complete. Participants were instructed to focus on the centre of the screen. Five arrows appeared in the centre of the screen (e.g. >><>>) and participants were asked to respond to the direction that the central arrow pointed to (pressing the z key for left and the m-key for right). On around half of the trials, the arrow orientation was congruent (e.g. all pointing in the same direction >>>>>) and on the other half of the trials the orientation was incongruent (with the central arrow pointing in the opposite direction to the other arrows e.g. >><>>). During the interstimulus interval, a fixation cross was presented. The duration of the interstimulus interval randomly varied between 400, 600, 800 and 1000ms. The Flanker stimuli remained on the screen until participants responded. Participants were encouraged to respond as quickly and accurately as possible. In 12 practice trials, participants received feedback on their performance and the instructions remained on the screen. The main experiment involved 4 blocks with 24 trials each.

Self-report measures

At the pre-training, the follow up post-training and 4-week follow up, participants completed the following questionnaires on Qualtrics.

Cognitive Failure Questionnaire. The Cognitive Failure Questionnaire (CFQ) is a self-report measure for cognitive failures in everyday life (Broadbent et al., 1982). The 25 item scale had a 5 point Likert scale ranging from 0=Never and 4 = very often and is measuring every day cognitive failures such as "*Do you find you forget why you went from one part of the house to the other?*". A high score therefore indicates an increased propensity to distraction. The questionnaire has shown to correlate highly with real life experiences, e.g. higher workplace accidents and increased CFQ scores (Wallace & Vodanovich, 2003). The test has been reported to have good internal consistency (α =.89) test-re-test reliability over 25 and 65 weeks with coefficients of .85-.80 (Broadbent et al., 1982).

Adult ADHD Self-report Screener. Participants also completed an Adult ADHD self-report screener (ASRS-V1.1, (Ustun et al., 2017) which is a validated clinical diagnostic tool that consists of 6 items to reliably assess ADHD symptoms in line with the DSM-5 ADHD diagnostic criteria. Participants respond on 5-point scale, (0 = Never, 1 = Rarely, 2 = Sometimes, 3 = Often, and 4 = Very Often) to questions such as *How often do you have problems remembering appointments or obligations*?. A high score on the scale indicates higher levels of ADHD traits. The scale measures inattentiveness on four items and hyperactivity and impulsivity on two items. The sensitivity of positively predicting ADHD is at .94 and for a negative prediction at 23.5 (Kessler et al., 2007). Internal consistency of items was high (Spearman's rho ranged between .61-.79) and Cronbach's alpha was fair at .54 for the total scale, .57 for the inattentiveness scale and .59 for the hyperactivity and impulsivity scale (Silverstein et al., 2018). The overall scale was test-re-test reliability of .78.

Sensory Perception Quotient (SPQ; Tavassoli et al., 2014) is a shortened 35-item scale reduced from a 92 item questionnaire. The short version of the SPQ has high internal consistency and assesses fundamental sensory experiences in autistic individuals across sensory domains. The scale assesses sensory experiences without assessing affective and behavioural sensations towards the sensory environment (e.g. such as frustrations towards noises). Questions include, for example*, I would be the first to hear if there was a fly in the room*. Responses were given on a 4-point Likert-type scale (1 = strongly agree to 4 = strongly disagree). Low scores on the SPQ indicate sensory hypersensitivity. The SPQ shows excellent reliability (α = .93) and moderate concurrent validity (*r* = −.49, *p* =.007) with the Sensory Over-Responsivity Scales (Schoen et al., 2008).

Multidimensional Assessment of Interoceptive Awareness MAIA Version 2 is a 37 item scale on a 5 point Likert scale ranging from 0 (Never) to 5 (Always; Mehling et al., 2018) and includes eight subscales that were further developed based on the first edition of MAIA. MAIA-2 measures interoception based on the subscales of noticing, not-distracting, not worrying, attention regulation, self-regulation, body listening, and trusting. Cronbach alpha ranged from .64 to .83 for the eight subscales. The questionnaire uses questions such as "*When I am tense I notice where the tension is located in my body*" or "*When I bring awareness to my body I feel a sense of calm*" to assess interoceptive awareness. High scores on the scale indicate an increased interoceptive awareness.

The Depression and Anxiety Stress Scales (DASS-21, Lovibond & Lovibond, 1995) was used as it is thought to reliably assess depression (α=.96), anxiety (α=.84) and stress (α=.93; Brown et al., 1997). The scales assess the acute symptoms "over the past week" with 7 items per subscale. Participants respond on a four-point scale (0= did not apply to me at all; 1= Applied to me to some degree, or some of the time; 2 = Applied to me to a considerable degree or a good part of time; 3 = Applied to me very much or most of the time). High scores indicate increased levels of depression, anxiety and stress. Previous studies have found that contemplative training a form of meditation can improve interoceptive awareness

(Bornemann et al., 2015). The scores were multiplied by 2, in line with the scoring manual of the DASS-21.

Written responses on meditation experience

To understand the participants' perceptions of meditation in general, and their experiences of the meditation programme, a few open ended questions were added. At baseline participants were asked "*Please describe your overall attitudes towards meditation, including any past experiences with meditation.*" and encouraged to write a few sentences on their experience. Post training participants were asked "*Please describe whether you noticed any changes as a result of the meditation programme on your attention, focus or well-being over the last two weeks. Please comment in up to five sentences.*" and "*Please add if there is anything you would like to mention after you completed with the training study? For instance on the flow of the study, the enjoyment of the meditation practice etc. Did you notice any changes as a result of completing the training (on physical, social, relationships, emotional functioning/wellbeing and thinking skills)?*". Together these questions were aimed to complement the quantitative findings and help assess the acceptability by the participants.

Data analysis plan

Qualitative data analysis

The written responses to open-ended questions about the experiences and attitudes towards meditation pre- and post-training were considered as qualitative data. Although there is a debate whether written data can be considered as qualitative data, recent precedent set in meditation research exploring experience of using neurofeedback devices was followed here (e.g. Hunkin et al., 2020). A content analysis was conducted on the participants' attitudes and experiences prior to taking part in the study. A content analysis allows to systematically code and categorise data exploring frequencies and structures within the data. This approach allows to quantify trends within textual data (Vaismoradi et al., 2013). An inductive approach to analyse the written responses was most appropriate to assess the qualitative prior experiences and attitudes towards meditation. The content analysis followed the suggested phases by Vaismoradi et al. (2013) to ensure the trustworthiness and credibility of the categories. I initially read through the content and hand coded each meaning unit. Subsequently, using Nvivo 12, the meaning units were constructed, classified and labelled. I applied the codes to the raw data again (rectification phase) and in the finalisation phase I wrote up the results. As the content was broad about participants' prior meditation experience, therefore only data on the barriers to meditation were analysed. An additional summative content analysis on positive, negative and neutral attitudes was extracted.

The qualitative written responses were analysed on the experiences on participating in the study a reflexive Thematic Analysis (Braun & Clarke, 2006, 2019) following an inductive (bottom up) approach. The six steps for the Thematic Analysis published by Braun and Clarke (2006) were followed namely; 1) familiarisation with the written data excerpts, 2) generating initial codes, 3) searching for themes, 4) reviewing themes and 5) defining and naming themes and 6) producing a written report.

In addition, to ensure that the anonymity of the participants was maintained new ID numbers were assigned and identifying information were removed from the analysis. Grammar and orthography in the written responses were corrected if necessary. The written statements ranged from a word to a short paragraph.

The codes developed for the qualitative content analysis and thematic analysis were completed by me, however the codes were checked by an experienced qualitative researcher (A.R) independently to ensure reliable categories. Two naïve researchers were presented with the materials and coding categories and asked to code 10 % of the material separately. Interrater reliability was 75%. As qualitative analysis is based on the researcher's own perspective, previous studies have highlighted that it is important to understand the analysis with the researcher's perspective in mind. The qualitative data was analysed by me from the perspective as a non-autistic researcher with no regular experience in using meditation or neurofeedback techniques. In addition, I position myself as a researcher who views autism as a social model of disability (Oliver, 1983), that seeks to improve the lives of autistic people and places the emphasis on adjusting the environment to meet the needs rather than seeking for the autistic person to meet the adjustments in the environment.

Quantitative Data analysis

The quantitative data analysis was preregistered with the OSF (https://doi.org/10.17605/OSF.IO/5NCY2). The 4-week follow up data was not usable because of the onset of the COVID-19 pandemic, only the pre- and post- intervention data were included. Independent samples t-tests were conducted to assess group differences at baseline for the executive function and self-report questionnaire data. Mixed analysis of variances (ANOVA) with within-subject factors of time (two levels: pre and post training) and group as between-subject factor were conducted to confirm whether there were any group differences in the meditation study. Mean reaction time for correct trials, and accuracy for congruent and congruent trials were calculated for the Flanker task. Similarly, for the Task Switching paradigm for switch and no-switch conditions I calculated the reaction times for correct trials and accuracy rates. For the Corsi block tapping task, the average trial length for each participant was calculated as well as the length of each individual trial to analyse performance over time.

Results

Adherence to training

The meditation training was completed by a total of 47 participants, and additional five participants started the training but did not reach the required minimum meditation time of 100 minutes (n=4 in the active control group and n=1 in the experimental group). The excluded participants in the active control group reached between 60-90 minutes of training and the participant in the experimental group meditated 90 minutes. In the experimental condition, participants reached a mean of 130.37 minutes of training (*SD*=14.92). Similarly in the active control condition, participants meditated on average 136.50 minutes (*SD*=12.26).

The groups did not significantly differ in the minutes they meditated ($t(45)=1.41$, $p=.17$). Three participants, one in the headset condition and two participants in the control group, received email reminders after they missed two consecutive days of meditation training.

Previous meditation experiences and barriers to meditation

In total, 46 out of the 47 participants (97.87%) responded to the open-ended question on their previous meditation experience and overall attitudes. A qualitative content analysis was conducted to assess the overall attitudes towards mediation experiences and barriers to engaging with meditation experiences. Overall the attitudes towards mediation were mixed; 12 participants (25.56%) reported to have a positive attitude, whereas nine (19.17%) participants' attitudes were neutral. Other participants were sceptical and had negative attitudes towards meditation (n=15, 31.91%), whereas 10 participants (21.3%) did not express their attitudes towards meditation. Most participants had some experience with meditation in the past such as during Yoga classes, in school or prescribed self-guided meditation at home.

Three main categories emerged from the data for barriers to meditation training in the past: 1) inability to focus 2) distracting environment, 3) scepticism towards meditation. Table 9 indicates the themes and seven codes that emerged within the categories. Three codes *not finding a routine*, *mental chatter* and *uncomfortable focus of breath* fell under the category of *inability to focus*. The category distracting environment was further subdivided into *others in class (social distraction)* and *hyper awareness of the sound scape* in the class or of the smartphone application. In the final category scepticism towards meditation further two codes encompassed the *illogical and abstract instructions* and the *scientifically unfounded* nature of meditation. A more comprehensive table with quotes can be found in the appendices (Appendix A, Table 11).

Table 9. Category and coding scheme for the barriers on meditation engagement with frequencies and percentages

Category	*Codes*	*N*	*%*
Inability to focus		*18*	*(38.3)*
	Not finding a routine	*5*	*(10.6)*
	Mental chatter	*10*	*(21.2)*
	Uncomfortable focus on breath	*3*	*(6.36)*
Distracting environment		*5*	*(10.6)*
	Social distraction	*2*	*(4.4)*
	Hyperawareness of soundscape	*3*	*(6.36)*
Scepticism towards meditation		*5*	*(10.6)*
	Illogical and abstract instruction	*2*	*(4.4)*
	Scientifically unfounded	*3*	*(6.36)*

Inability to Focus. A large group of participants explained that that they found it difficult to either start or maintain the focus on the meditation practice.

Not finding a routine. Participants frequently reported that they “do not get the time or forget” (C16) to meditate and “failed to keep it up” (H18) and it was difficult to find a routine to engage in and maintain it over time. One participants commented:

> I would like to meditate. I have sometimes tried using an app in the past. I am terrible at consistently implementing new routines e.g. I have never managed to make tooth brushing a regular part of my routine, I understand the need for dental hygiene, I just can’t regularly do it. H4

Mental chatter. Participants frequently report that they found themselves daydreaming, unable to quieten their mind and “difficult to concentrate” H22, one participant mentioned that it was difficult to “redirect the constant flurry of thoughts“C7 and remain focused on the meditation practice. Another participant commented “My mind races 110% of the time. I would welcome a break from my own thoughts” (C19).

Uncomfortable focus on breath. Participants reported that they felt that the focus on the breath was unnatural and uncomfortable to them. “I found it difficult to concentrate on. And I worry about focusing on my breathing too much in case I breathe too fast or forget how I'm supposed to breathe.” H22. One other participants mentioned that the focus was on the breath was unsolicited “I don't particularly want to listen to my breathing.” (H2).

Distracting Environment. Other barriers were related to external factors that made it hard for participants to engage in meditation training in the past.

Social distraction. The nature of meditation as such that took place as a social setting in the class- or 1:1 setting made it difficult for some participants to focus on. In particular participants reported on their anxiety to be in a room with other people. Whereas another commented that the barrier of a taking part in a group based meditation setting would be high “I have never had the chance to part take as there would be too many people there. Also they would annoy me and I would be easily put off.” C10

Hyperawareness of soundscape. The soundscape was frequently mentioned as distracting, whether that was based on meditation experience in a class or when using a meditation smartphone application. One participant commented that “I used to try meditation with a group [...]. I always struggled to keep concentration with the noises in the venue and the movements of others. […]” suggesting that the distraction occurred from within the room. Another participants concerns were to related to the voice of the meditation facilitator “Tried once in past following a body scan meditation but just didn't engage, found the person's voice annoying. If the sound bugs me then I won't be able to engage in it, and sitting in silence and trying myself wouldn't work either.” This shows that the circumstances of the meditation had created barriers for the participants specifically.

Lastly, the remaining category was focused on *scepticism towards meditation* and voiced around the unscientific nature of meditation and lack of pattern.

Illogical and abstract instruction. A few participants have noticed that they were “quite sceptical of mediation or mindfulness having any positive impact as it seems to abstract and impossible.” (C1). Another participant highlighted that when trying to meditate previously the instructions were inconsistent.

> *“Honestly I'm not too sure what it involves. I was given a relaxation tape […] I thought it was a bit illogical as it talked of legs getting heavy and weighed down etc. and they were the same as they were before. However I would like to retry it and see if it does work.” (H8)*

Scientifically unfounded. A couple of participants also questioned the scientific foundation for meditation and where one participant raised concerns that it is “a bit gimmicky and 'hippyish'. (C5) and another commented on the larger therapeutic application of meditation in the health care sector “it is being framed as a solution to mental health problems in the absence of proper funding of mental health care.” (H3)

Thematic analysis on the experiences post meditation

Themes and subthemes that emerged from the written open ended questions that participants completed post meditation training are presented in Figure 24. A more comprehensive table with illustrative quotes for each theme is provided in the appendices (see appendix B, Table 12). There were no overall differences in the themes that emerged in each of the groups, the results are combined and the identity number indicates the group membership (H= headband group and C= control group).

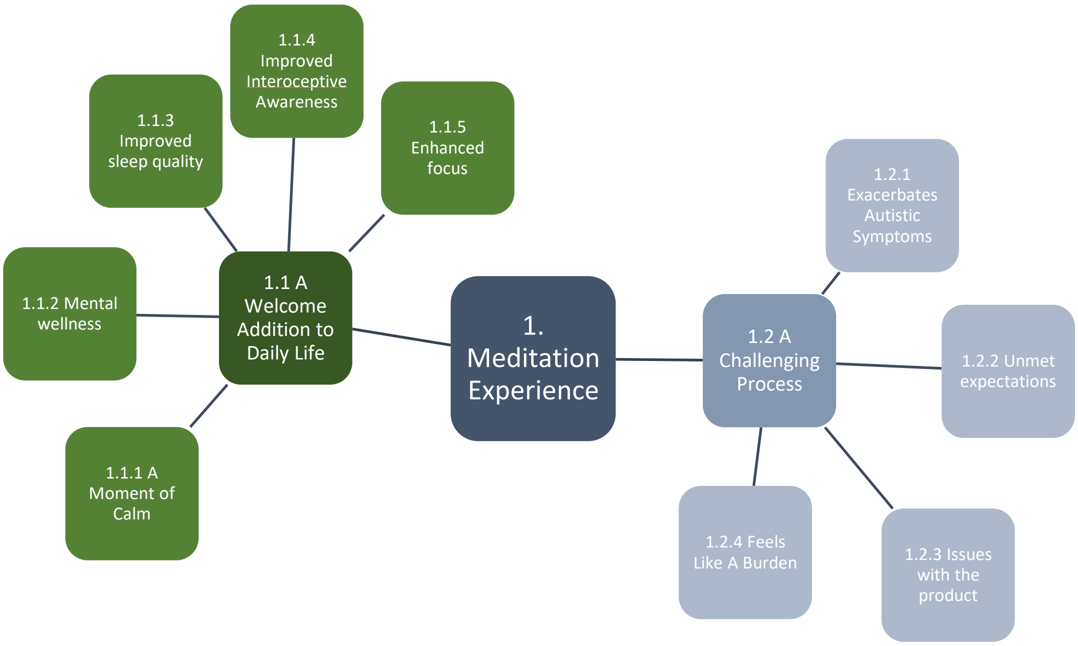


Figure 24. Thematic map for meditation experiences collected after completing the 2-week training

Overall, two main themes emerged. Some participants reported that the meditation training was a positive experience and *a welcome addition to daily life*. Whereas other participants reported that the training was *a challenging process* and highlighted difficulties that participants experienced as a result of the training programme. These categories were not mutually exclusive, for instance whilst participants had positive perceptions (e.g. improved wellbeing) but still felt like it was a chore to complete it every day.

1.1 Theme: A Welcome Addition to Daily Life

This theme involves the positive experiences that participants reported in relation to the enjoyment of the training, the impact on wellbeing and focus it brought them.

1.1.2. Subtheme: Moment of Calm

Positive experiences were linked to the adoption of a regular routine in which participants describe that they enjoyed taking 10 minutes a day for themselves was helpful.

One participant commented on that they enjoyed the sessions: “I looked forward to my session every evening” (H9), similarly another participant commented that the anticipation of the practice made them feel better “Knowing I had 10 minutes of "just be" time coming up did make me feel more calm” (C6). Furthermore, as noted by the participant (C6) the feeling of just being and removing themselves felt good, other participants seconded this experience and stated “I did notice that I liked the 'excuse' it gave me to remove myself from everything for 10 minutes every day.” (H5).

Others noted that the programme that the programme gave them some incentive to stay motivated. “I really enjoyed the meditation for 14 days. It was good having the motivation of the study to push me to do it each day” (H22)

One participant noted that the meditation helped them to get in the right mind-set, when they did not feel well: “Sometimes, my emotional states made it hard to keep calm, but even then meditation helped me to relax.” (H11)

However, a small number of participants noted that a certain level of calmness was needed to effectively meditate: “There were a couple of sessions where I was already more relaxed and the meditation worked better then.” (H2)

1.1.2 Subtheme: Mental Wellness

Participants noted that the mediation training improved their overall perceived wellbeing. One participant noted that the meditation has improved their mood and motivation. They also noted that their anxiety and pain levels have reduced as part of the meditation practice, the effects were also noticeable by other people.

> “I feel a bit more positive […] Often immediately after the ten minutes I felt more motivated. I've found I've had more fresh air and often it helps me almost reset to then get on with the rest of the day. I've also interesting taken less painkillers. I still get

> anxious too much but I wonder if I kept this up if this would lessen with time. Others have noticed a slight change for the better” (H8)

Another participant noted that they felt calmer and talking to other people about the training study has helped, to as a topic in social conversations:

“Overall, it has made me quieter and more relaxed. […]I feel in a good shape, and explaining I meditate has helped me to do social chit-chat with people.” (H11)

Likewise, another participant reported that they were motivated and enjoyed to take time for their family. Also dealing with stress, emotions and overload was improved:

> “Felt a lot calmer, clearer in my mind, reduced incidences of being overwhelmed or hopeless, got a lot more done. Have enjoyed playing card games with my daughter which I would not have had the energy to do before.[..] Emotionally I have felt calmer […]. I have dealt with stressful events better and have had less incidences of overload.” (H15)

1.1.3. Subtheme: Improved sleep quality

A group or participants noted that the meditation practice helped them to fall asleep better: “It sends me to sleep better.” (H19). Another participant also noted that they found a routine of meditating before going to sleep: “I definitely slept better. It also gave me a bedtime routine.” (H9).

Likewise, another participant commented on that they found a routine as they progressed with the meditation study that helped them to feel less overwhelmed by the meditation “though I did feel that it benefited me sleeping. In the last week(ish) I did it right before bed and once I was in this routine, it was far less of a chore and caused me less worry/stress.” (C14)

1.1.4 Subtheme: Improved Interoceptive Awareness

A few participants reported that they focused on their breath more in other situations, outside of the meditation training. “I feel pretty restful and found I have paid more attention to my breath now” (H26). Other participants reported that the increased awareness of their breathing helped to deal with anxiety “Also found myself slowing my breathing down when I was getting too panicked.” (C8)

Interestingly, at the same time, a few participants noticed that they found an overall interoceptive awareness improved for wider bodily sensations:

> “I noticed I could more easily think about my body and be aware of it. I also noticed I was more able to figure out what was wrong with my body, rather than just noticing it. For example, if my body felt bad, I was more easily able to work out of that pain was hunger, tiredness, illness, etc” (C2)

Likewise, another participant noticed that the ability to focus on the body and breathing has helped to distinguish between physical sensations better:

“I've found the focus on breathing helpful and sometimes can then work out if its a physical sensation that is wrong e.g. I'm hungry rather than just feeling of panic.[…].” (H8)

1.1.5 Subtheme: Enhanced focus:

Participants report an improved ability to concentrate in daily life and have and clarity to varying degrees “seem to be slightly more focused.” (C13) and another commented a “General boost in attention span” (C8). Another participant has noticed that their attention improved:

“Felt a lot calmer, clearer in my mind, reduced incidences of being overwhelmed or hopeless, got a lot more done. Increased clarity and able to focus and prioritise the last couple of weeks” (H15)

1.2. Theme: A Challenging Process

This theme refers to the challenges and negative experiences that participants reported as a results of the meditation training.

1.2.1 Exacerbates Autistic Symptoms

A few autistic people reported that meditation was not compatible with their cognitive processes, one participant reported that “I wonder if overthinking/my brain going very fast, is better than the calm that meditation brings” (C18), similarly another participant that it felt that the meta-cognition and redirection of thoughts was unhelpful “I think that forcing my brain to think of anything besides what it was naturally inclined to think about caused similar stress to when my routine is interrupted or I'm disturbed when trying to complete a task.” (C11). Importantly, participants reported that they enjoy the constant brain activity and is not compatible with autism.

> "I don't want to just focus on one thing when I have several exercises, debates, planning discussions and pattern-noticing activities going on in my head most of the time. I like the activity in my head, especially now that I am happier about having it and less concerned that it is a problem […]. It feels like meditation is meant for non-autistic people who might want to empty their brains and focus on their sensations." (H2)

1.2.2 Subtheme: Feels Like a Burden

A few participants “found the meditation a bit of a chore” (H18) and it was difficult to find a routine. Similarly, “Remembering to take part in the programme with the daily time limit (i.e. must do it before midnight each night) was somewhat stressful/another chore in it's own right” (C14).

In addition, one participant found that 10 minutes were too long each day, “I would have preferred 2x 5minutes as I struggle to relax for the whole 10 minutes” (H12) and another participant in the control group reported that the lack of guidance made it hard to concentrate for 10 minutes.

> “I've had trouble focussing on the meditation and wonder whether guided meditation would help me more specifically. I think having 10 minutes of silence (background sound) lead more to my brain doing what it wanted, whereas the guided type would be telling me what to do. I found it very difficult to remain focussed on my breath […]”(C12)

Focussing on breathing was also difficult for some participants, “the physical act of listening to my breath was very, very hard.” (H7) and another participants commented that this escalated “My ability to maintain focus on my breathing rather than thoughts got gradually worse throughout the two weeks.” (C11)

1.2.3 Subtheme: Unmet expectations

The meditation training has not had the desired or anticipated effects, one participant said they “do not feel it has had the impact on me that I expected.” (C6). Another participant hoped that “meditation would be a new tool to manage stress and anxiety, but now I'm wary of it” (C19) when the effects did not match their expectations. One participant in the headband group mentioned that: “I didn’t really understand what meditating was. I followed the instructions but couldn’t spot any patterns. The sounds of the weather was sometimes calm and sometimes stormy but I couldn’t spot the pattern about what was controlling it.“ (H4)

1.2.4 Issues with the Product

The technology related to the smartphone application and the headband led to issues for some participants. The soundscapes were in particular an issue for participants in both groups and selecting the right was important “The soundscapes were hugely important in my experience: some really prevented me from getting calm.” (H11). Whilst one participant found that “The sound effected how relaxing I found it. The beach and rainforest were most effective.” (H19), another participant mentioned that there were specific sounds that made it difficult to focus:

> “[…] [I] found the noise track had another layer (the noise was natural - the sea I think, but there was a rhythmic sound under that - no idea what it was, but so distracting I couldn't use headphones).” (C15).

Another participant also noticed that there was a distracting sound in the soundscapes and called for improved customisation of the product: “I tried hard to focus on it and do my best not to hear the sound that found annoying [..] also the fact [that you] cannot change the voice of the person speaking” (C11).

There were some specific aspects of the neurofeedback device that some participants in the headband group struggled with, in particular participants noticed that there the feedback was incongruent with their perceived mental state. “I was surprised by how much of the time my brain was shown to be in a calm state even when I thought I was distracted.” (H1) another participant noticed that the neurofeedback indicated the desired mental state for meditation indicated by birds tweeting changed with their breathe “[I] felt that muse would have birds if I stopped my breath which seems counterintuitive” (H15), another participant perceived similar dissociations between their perceived mental state and the feedback as well as raised issues around the transitions between soundscapes:

> *“I found the Muse Headband and the 'weather' effect was changing with my breath so it was actually distracting from practice, and the transitions between sounds was sometimes not very well presented with the audio so this could use some calibration and polish. I had hoped this would improve with longer use but it did not improve over the 14 sessions, it did not seem to pick up when my mind was calm and focused. […] (H27).*

Baseline data

Independent samples t-tests indicate that at baseline the groups did not significantly differ on self-reported levels of the DASS-21, ASRS, MAIA, CFQ and SPQ, nor did the groups differ on the executive function task at baseline (the p-values and means in standard deviations in Table 10).

Executive function tasks

Flanker Task

To investigate differences on Flanker accuracy, ANOVAs were carried on data pre- and post-training. There was a main effect of congruency ($F(1,43)= 24.28$, $p<.001$, $\eta^2=.13$), suggesting that participants were more accurate during congruent compared to incongruent trials. The main effects of time and group, and all other interactions, were not significant (Fs<1). This suggests that there were no differences on the Flanker task over time, or between the groups (see Figure 25 and Table 10. Descriptive statistics for the self-report questionnaire data and behavioural performance variables by group at baseline and post training.

Similarly, for the reaction time data on the Flanker task revealed a main effect of congruency ($F(1,43)=88.68$, $p<.001$, $\eta^2=.004$), suggesting faster reaction times on congruent trials compared to incongruent trials. The main effect of time ($F(1,43)=2.10$, $p=.15$, $\eta^2=.01$), group ($F(1,43)=1.45$, $p=.23$, $\eta^2=.03$) and interactions (Fs<1) were insignificant, indicating that there were no reaction time differences neither between the groups nor over the two time points.

Task switching

Task switching data was excluded for one participant as the accuracy rates were below chance pre- and post-training. This suggests that either the task instructions were not understood or the participant was unable to perform the task for some other reason. For the accuracy rates the main effect of task condition was significant ($F(1,39)=17.34$, $p<.001$, $\eta^2=.03$), which indicates that accuracy rates were higher on trials were participants did not have to switch task conditions (for means and standard deviations see Table 10). The main effect of time ($F(1,39)=3.92$, $p=.055$, $\eta^2=.02$) was insignificant. The main effect of group and all other interactions were insignificant (*F*s<1).

For the reaction time data, similar to the accuracy rates, there was a main effect of task condition ($F(1,39)=7.88$, $p<.001$, $\eta^2=.001$). Participants were slower on trials where the task instruction changed compared to the trials were the instructions remained the same. The main effect of time (F(1,39)= 1.2, p=.28), group (F(1,39)=1.36, p=.25) and all other interactions were insignificant (*F*s<1).

Corsi Block Task

As the Corsi Block tapping task was adaptive to participants' performance, all participants started off at set size 3. The average set size that was presented in the adaptive task for each participant was calculated, the first 6 trials were taken out of the analysis, to allow participants to reach their personal asymptote. The mean set sizes were entered into a ANOVA with group as a between subjects factor (2 levels: headband vs control) and time as a within groups factor (2 levels: pre and post training). The results indicated that there was no main effect of time, group or interaction (F*s*<1), suggesting that the training did not make a difference for the Corsi Block Task.

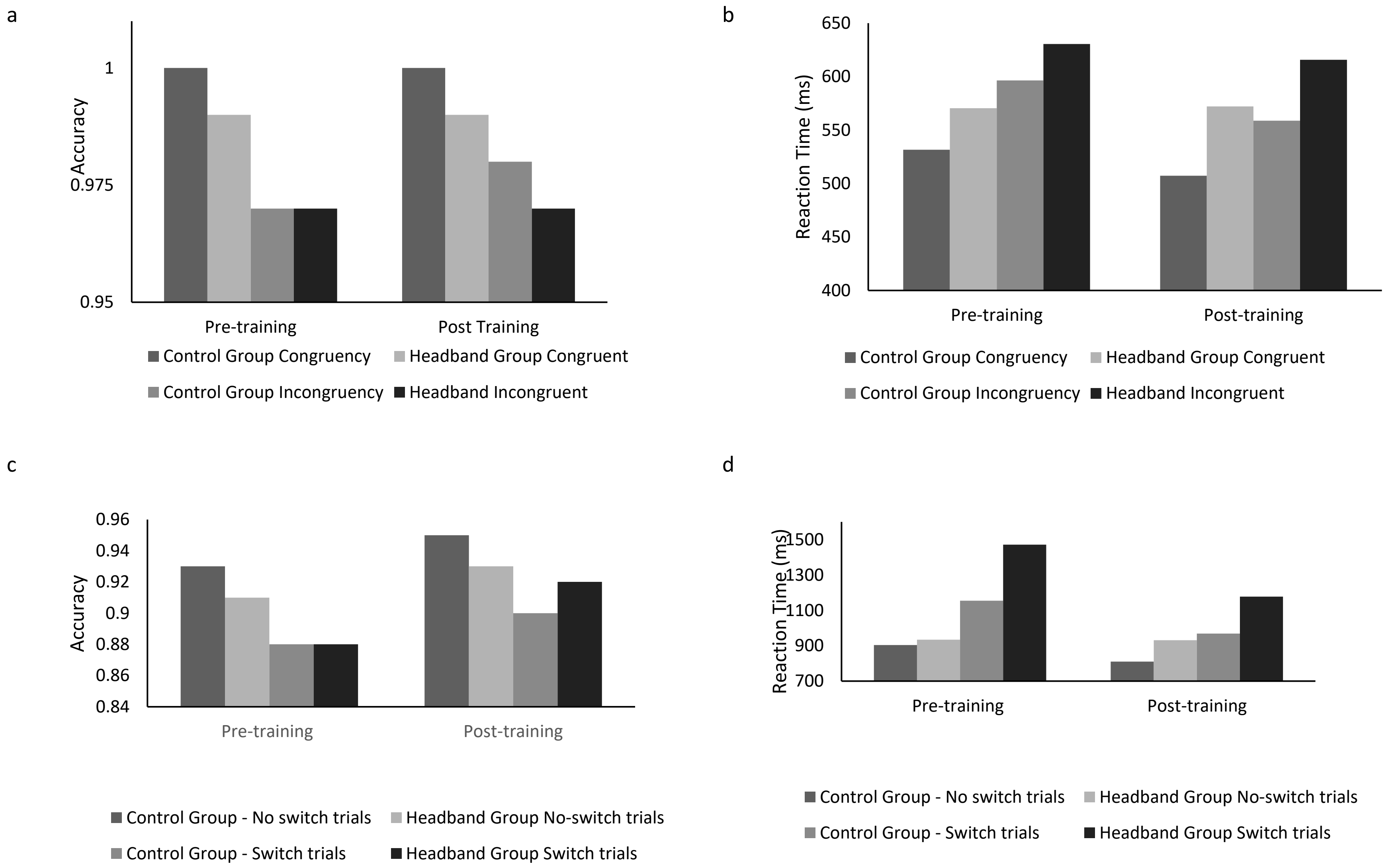


Figure 25. Performance for a) accuracy and b) reaction time for the Flanker task, c) accuracy and d) reaction time for the Task Switching paradigm

Table 10. Descriptive statistics for the self-report questionnaire data and behavioural performance variables by group at baseline and post training.

	Headband Group						**Control Group**						
	Baseline			Post-training			Baseline			Post-training			Group difference Baseline
	N	*Mean*	*SD*	*N*	*Mean*	*SD*	*N*	*Mean*	*SD*	*N*	*Mean*	*SD*	*P-value*
DASS	27	64.52	(31.78)	24	43.26	(28.76)	20	68.4	(34.06)	19	48.98	(27.08)	.69
MAIA	27	70.78	(23.02)	24	71.25	(29.22)	19	82.32	(25.21)	19	83.74	(20.63)	.11
SPQ	27	31.11	(14.78)	24	32.38	(16.13)	20	36.15	(13.35)	19	33.63	(14.79)	.24
ASRS	27	14.19	(5.72)	24	12.79	(5.52)	20	13.65	(3.3)	19	11.68	(3.97)	.71
CFQ	27	61.07	(22.33)	24	56.25	(21.3)	19	61.79	(20.68)	19	49.32	(21.64)	.91
Flanker ACC (congruent)	27	.99	(.02)	26	.99	(.02)	19[a]	.97	(.04)	20	1.00	(.01)	
		.92-1			.92-1			.89-1				.94-1	
Flanker ACC (incongruent)	27	.97	(.04)		.97	(.04)	19	.97[a]	(.04)	20	.98	(.023)	.49
		.83-1			.89-1			.89-1				.89-1	
Flanker RT congruent (ms)	27	570.45	(135.04)	26	572.23	(133.37)	19	531.64	143.10	20	507.40	(121.60)	
		408.33-942.98			425.22 -1050.81			370.48-863.36				371.01-809.49	
Flanker RT incongruent (ms)	27	630.61	(144.29)	26	615.75	(150.02)	19	596.46[a]	(133.00)	20	558.80	(127.61)	.38
		479.23 - 1022.484			481.52-1164.96			453.20 – 890.25				449.-858.67	
Task Switching switch trials ACC	26[b]	.89	(.12)	23	.92	(.1)	19[a]	.87	.13	19	.9	(.08)	
		.52-1			.62-1			.55-1				.68-1	
Task Switching no switch trials ACC	26	.92	(.13)	23	.93	(.09)	19	.92	(.10)	19	.95	(.07)	.79
		.46-1			.71-1			.65-.1				.74-1	
Task Switching, switch trial RT (ms)	26	1441.63	(1647.18)	23	1176.86	(835.29)	19[a]	1126.63	(540.23)	19	955.82	(277.36)	
		475.81-9333.14			444.53-4857.39			569.85-2825.64				622.82-1500.87	
Task no Switching RT ms)	26	945.05	(302.99)	23	930.68	(359.68)	19	881.32	(321.48)	19	802.97	(190.38)	.39
		406.57 – 1498.29			446.84-2235.85			474.08-1760.15				571.91-1314	
Corsi-Average set size	26[c]	4.23	(.98)	25	4.31	(.78)	20	4.39	(.89)	20	4.37	(1.09)	.95
		3.13-5.43			2.3-5.7			2.37-5.77				1.43-6	

Note. [a]*Data missing for one participant for the Flanker and Task switching data due to a technical error;* [b]*data removed for task switching as performance was below chance for pre- and post- measures due possibly due to technical error where task did not load.* [C] *Data taken out as only 3 trials of the Corsi task available.*

Self-report data

Separate mixed ANOVAs were conducted for the self-report data (DASS, ASRS, CFQ, SPQ, MAIA) with time as a within-subjects factor (2 levels: pre and post) and group (2 levels: experimental group vs active control group) as a between subjects factor. There was a significant main effect of time for the DASS-21 (*F*(1,41)=10.46, *p*<.001, η^2=.10) with a reduction in the DASS-21 scores for both groups when comparing pre- and post- training data (see Table 10). All other main effects of time were insignificant (CFQ: *F*(1,40)=3.07, *p*=.09, η^2=.003; ASRS: *F*(1,41)=2.92; *p*=.09, η^2=.003 and all other self-report measures (*F*s<1)). Furthermore, no main effect of group (*F*s<1) nor interactions between time and group in any of the self-report measures (*F*s<1) were observed.

Discussion

The present study assessed the feasibility of a neurofeedback meditation intervention and an active control group in autism. Two trial arms were used in the present study to understand the feasibility of an online intervention trial and whether the guidance through neurofeedback and a self-guided smartphone application tool had an impact on executive function or mental health. More specifically, the aim of the present study was to assess the feasibility of the neurofeedback and smartphone guided meditation intervention in autistic participants who were novices at meditating. The feasibility was assessed using compliance rates and open ended-questions prior and after the training to understand people's experiences of mediation. In addition, I assessed the effectiveness in improving shifting, updating and inhibition in executive function tasks and the impact of meditation on self-reported mental health, interoception and sensory experiences. Overall, the study indicates that although compliance rates were high, participants indicated their experiences was mixed. There were no differences in cognitive performance before and after the training study, however on average self-reported depression, stress and anxiety decreased as part of the meditation training. Each of the results will be discussed in more detail below.

Feasibility of the meditation program

The qualitative data are a rich way to investigate people's experience and assess perceived feasibility of the meditation programme. Previous research highlighted the importance of prior expectations and motivation in training studies (e.g. Denkinger et al., 2021). Importantly, the levels of scepticism was however high (around 1/3 of the participants reported that they were sceptical of meditation prior to participating), thus the present sample might have involved a larger group of people who would have not normally taken part in meditation research.

The findings of the present study produced mixed findings on barriers to meditation. Participants stated the barriers that prevented participants from taking part in meditation previously. To understand participants' previous meditation experience and barriers, three themes emerged. Firstly, in line with the scepticism towards meditation, some participants were wary of the scientific nature and abstractness of the meditation training. In addition, the lack of time and or concentration has prevented them from taking up meditation. Interestingly, soundscapes in the class setting or the voice of the instructor on the smartphone application that delivered the meditation training as well as anxiety prevented them to take up meditation in a group setting in the past. Thus, understanding common barriers can help to target intervention trials and make them more comfortable and convenient for participants.

Importantly, as the study is the first to explore a neurofeedback meditation intervention in autism, qualitative data was used to capture the experience after taking part in the study. Two main themes emerged, where participants reported that the experience was positive and a benefit for their day to day life and another theme that captures the challenges that participants faced in the process. The positive experiences were related to perceived aspects of improved mental health, focus or sleep, in line with previous reported literature in meditation (Goyal et al., 2014). Interestingly, contrasting evidence was found for the routine, whilst some participants reported that they benefited from the routine that the meditation programme brought them other felt that the routine was a chore and burdensome. This indicates that there are stark individual differences across participants. However, no systematic group differences were evident in the perceived experience relating to the routine or any other themes.

Another challenge reported by participants was that they anticipated that the meditation training could help them with specific aspects of life and emotional processing. However, participants expressed frustration when expected changes did not occur. Similarly, worsening of symptoms for a small group of participants have been reported in the present sample. This is in line with recent findings from qualitative studies that indicated harmful side effects of meditation for a subgroup of participants. For instance Cebolla et al. (2017) found in a sample of 342 participants using a content analysis that a small number of participants have reported worsening of mental health aspects, dizziness and an impact on vision. It is therefore crucial to investigate negative side effects in training studies and qualitative studies might be better equipped to do so. Thus, the causes should be carefully studied and better pre-screening methods have to be developed to avoid adverse experiences for participants. Interestingly, the findings align with a recent neurofeedback that identified positive aspects and barriers to meditation (Hunkin et al., 2020). Interestingly, when exploring the open ended questions about the meditation experiences in a population of students, Hunkin and colleagues (2020) reported that some participants mentioned that the meditation experience was positive, however others mentioned that is was stressful to look at the neurofeedback that was provided, distracting and the feedback they received was incongruent with their experiences.

In the experimental group, participants reported frustration at setting up the Muse meditation headband and described it as uncomfortable but also producing auditory feedback mismatched with the experienced meditation. Previous studies indicated that the dry sensors integrated in the Muse headbands are at risk to artefacts related to muscle movement and movements related to the breath cycle and therefore produces inconsistencies with the experienced meditation state (Acabchuk et al., 2020; Ratti et al., 2017; Wexler & Thibault, 2019). Similar qualitative feedback was also produced by other neurofeedback interventions using the same neurofeedback device (Hunkin et al., 2020). The headband used in the present study was however not the latest model and it is unclear if the inconsistencies reported translate to more recent models. The soundscape were challenging for some participants who reported that some unnatural sounds made it challenging to relax. In line with the qualitative pre-meditation data, participants frequently report that the soundscape was not suitable or distracted them. This could be related to the sensory experiences that are often reported to be atypical in autism (Crane et al., 2009) and make the engagement in the meditation training more challenging. A few participants suggested a larger selection of sounds and customisation of the soundscapes to address the issue.

The study had high compliance rates for the participants who started the meditation training (experimental group: 90% and active control group: 90.90%). Although, it has to be noted that 4 participants in the experimental group and 8 participants in the active control group did not start the training after receiving the training information. It is unclear why those participants chose to withdraw from the study at that stage. For the participants who started the training programme the daily compliance rate for the daily engagement in the programme were high, however five participants did not meet the required 100 minutes of training to be considered to have completed the meditation programme. This suggests that even though the study was delivered online, compliance rates suggest that the study was feasible. Importantly, taken together evidence from previous studies that suggest that compliance is higher in autistic compared to non-autistic adults (e.g. Chandler et al., 2019), and the mixed perceived benefit of meditation, extra care has to be taken when designing intervention studies for autistic people. For instance, frequent monitoring of participants as well as using a mixed methods approach can help to design better interventions and understand the heterogeneity amongst the reported experience further.

Improved Self-Reported Mental Health?

Crucially, participants reported a reduction of self-reported depression, stress and anxiety symptoms as measures on the DASS-21. The reduction of self-reported mental health scores (M= 21.3) was significant (with medium effect sizes in the neurofeedback *d*=.50 and control group d=.52). These findings are not surprising given the meditation literature that details benefits on mental health (e.g. Goyal et al., 2014). The improved self-reported DASS-21 scores, are also in line with a recent study that found a reduction in mental health (DASS-21) scores in the neurofeedback and an active control group that used a smartphone meditation intervention (Acabchuk et al., 2020). Likewise, Gaigg and colleagues (2020) reported a reduction in self-reported anxiety in a waitlist randomised control self-guided meditation trial with autistic participants. It is important to note that the benefits of meditation of mental health was evident for both groups and there seem to be no added benefit for one group or another. The improvements in mental health scores could indicate a regression to the mean, the pure effect of being enrolled in the programme might have led to a reduction in mental health score. All other measures such as interoceptive awareness, sensory experiences, cognitive failure questionnaire and the ADHD screener did change for either of the groups as a result of the training.

Whilst the improvements of the mental health scores could indicate a potential avenue for therapeutic intervention in autism, the results have to be viewed cautiously. A strength of the present study is the use of the mixed methods approach, which allows contrasting the open-ended data with the self-reported questionnaire data and cognitive tasks. Whilst *on average* mental health scores improved for both groups across the two time points for both groups, contrasting the findings with the overall qualitative data suggests that the meditation training is *helpful for some* participants' mental health, yet, meditation must not be regarded as an feasible treatment for the entire sample, and the meditation has even had an adverse impact on a few participants. Therefore, using mixed methods intervention and qualitative studies are warranted to explore how the training was beneficial for some and identify if meditation training could be made a safe therapeutic tool to improve aspects of mental health.

No Training Gains on Cognitive Function Tasks

The present study did not show any transfer effects for the executive function performance measures for either of the groups. One previous meta-analysis reported that the training gains were most visible on executive function tasks that required inhibition (Gallant, 2016). However, the review explored the findings on mostly pre-potent and not cognitive inhibition (see introduction chapter for distinction), and may not directly translate to the Flanker task used in the present study. Interestingly, other meta-analyses indicate that working memory improvements were most noticeable compared to other executive function tasks (Cásedas et al., 2020; Chiesa et al., 2011). However, a previous study used a machine learning approach to explored differences in cognitive training outcomes (Shani et al., 2019). The study indicated that individual characteristics such as cognitive performance, mental health, personality traits and age at baseline are predictive of training success. Therefore, in the present study training mental health issues at baseline were high and might explain why there were no gains for meditation training.

It has to be noted though that meditation training studies have received criticisms as the field is fairly new and therefore there are no consistent definitions or theories that are tested and conclusions are based on post hoc analysis, small sample sizes and lack of a sufficient control group or randomisation make the studies in the literature less rigorous (e.g. Tang et al., 2015). Additionally meta-analyses face challenges of methodological diversities employed with range of different meditation and mindfulness interventions and control groups, cross-section and longitudinal designs and including novices and experts making interpretations difficult (for a review see Davidson & Kaszniak, 2015) and might partly explain the differences found in executive function gains in meditation training.

As outlined in the introduction, meditation is thought to act on aspects of attention and meta-cognition, however the mechanism of meditation is still unclear. In the general cognitive training literature, the assumption is that through plasticity in the brain, domain specific training can lead to an increase in domain general cognitive skills (e.g. Karbach & Schubert, 2013). Whilst previous studies have reported gains through app and neurofeedback based meditation on executive functions, in the present study no such “far” transfer effects on executive function and attentional abilities were found. In fact, a recent review highlighted the issues of domain specific training – when the skill that is trained is specific – but transfer effects are expected on broader cognitive domains (Sala & Gobet, 2019). Thus, re-examining previous meta-analyses on transfer effects across domains Sala and Gobet (2019) found minimal transfer effects. Therefore, it might be more appropriate to train cognitive domains and not a far transfer across domains but rather test whether the improvements are specific.

As such, within-domain gains in sustained attention were observed in a 3D multiple object tracking intervention in autistic adolescents (e.g. Tullo et al., 2018).

Moreover, in the present study the daily and total length of training was relatively short (10 minutes for 10-14 days), however the intervention trials in the literature vary considerably in duration (for instance in a recent meta-analysis Cásedas et al., 2020 the duration of meditation ranges from 60-38200 minutes; mean 3641 minutes). Therefore, the length of the training might be important to achieve gains in cognitive performance and might be the reason why no differences were found between the two time points. However, available meta-analyses have not systematically explored the effects of the length of the training on cognitive outcomes. Although, there were reports of gains using neurofeedback were even short meditation interventions (20 minutes for 4 days) can improve cognitive and emotional states (Zeidan et al., 2010). Whilst the remote nature of the study enabled participants to take part across the UK, there are limitations to the uncontrolled environment of the baseline and follow-up data completion. For instance the visual angle of the presented object and data resolution cannot be standardised across participants. Importantly, the overall insignificant cognitive performance in the present study across might be related to the mixed qualitative feedback where some participants reported an improved focus that is in stark contrast of participants who reported memory and concentration issues as a result of the training.

Limitations and future directions

The onset of the pandemic and the national lockdown in the UK from March 2020 neither allowed the inclusion of data collected for the 4 months follow up nor open up the study to the participants on the waitlist to maximise the sample size. Therefore the sample size (n=47) of the study was moderate and the calculated a priori power was not achieved (for a minimum of n=50). In addition, no conclusions can be drawn about the findings over time.

The study assessed the duration of the meditation training as a marker of meditation engagement. Although not a primary aim of the thesis and not pre-registered, aspects of the quality of the meditation practice could be investigated through the activation of the neurofeedback headbands in the meditation group to explore whether there were specific aspects associated with the outcome of the meditation programme.

Interestingly, Shani and colleagues (2019) also indicated that parameters of the training and training engagement should be altered to fit participants personal needs. Therefore, fitting with the mixed preferences that emerged in the present study, future studies might employ a pragmatic clinical trial. Parameters could then be flexibly adopted and allow participants to select the duration of the training, the level of guidance in the meditation and whether that is administered in a smartphone application. Similarly customisations such as altering the soundscape in a smartphone application could help to ensure that individual needs of the participant are met and could lead to improved outcomes for the participants.

Chapter 6
General Discussion

Attention is a fundamentally important cognitive process and is required to efficiently navigate the world. Whilst attention modulations have been frequently observed in autism (Ames & Fletcher-Watson, 2010) the differences seen suggest that attentional processes in autism are different, however not necessarily deficient. In fact, aspects of superior visual perceptual abilities and enhanced perceptual capacity have been found. The goal of the present thesis was to further explore the previous findings of an enhanced perceptual capacity under the framework of the Load Theory and to extend the findings to more active components of the theory.

To address this aim, across the first three empirical studies I assessed selective and executive attention in autistic and non-autistic adults and the fourth study investigated the feasibility of a neurofeedback study. Specifically, in Chapter 2, I considered whether a manipulation of cognitive capacity analogous to an enhanced perceptual capacity would be increased in autism using behavioural markers of congruency effects. In Chapter 3 I investigated electrophysiological aspects of visual working memory capacity and filtering efficiency. The findings were further extended in Chapter 4 by directly contrasting visual working memory capacity and perceptual capacity using electrophysiological markers. Finally, I sought to assess whether practical steps could be taken to address altered attention experienced by autistic adults. The feasibility of an online neurofeedback intervention in autism and assess whether aspects of attention and mental health could be improved through the training programme (Chapter 5).

In the present Chapter, I will address and summarise the main findings from the experimental chapters of the present thesis. Subsequently, the contribution to the attention literature in autism will be discussed. Finally, I will outline the limitation of the presented work and make recommendations for future research to improve our understanding and elucidate mechanisms that can attention in autism.

Summary of Aims and Results

Enhanced Cognitive Control Capacity. The Load Theory predicts that different types of load have opposing effects on how stimuli are detected. When increasing perceptual load (e.g. increasing the perceptual demands of a task, such as a visual search task) distractor processing is reduced, as no additional resources are available to process task irrelevant information. When active processes are loaded – i.e., by manipulating the demands on cognitive load (e.g. on a memory task), distractor processing is observed to be increased, as there are no available resources to prioritise task relevant information.

Whilst autistic people show increased perceptual capacity (e.g. process more sensory information at any given time) the question remained as to whether this extends to the more active aspects of cognitive load. Previous indirect evidence in the inhibition and task switching literature suggest that autistic people have difficulties across both domains. However, selective attention ability under varying levels of cognitive load has not yet been examined.

In the first empirical study of this thesis, a multiple component visual discrimination flanker task similar to that of Brand-D’Abrescia and Lavie (2008) was used to assess selective attention under high and low levels of cognitive load. Participants were asked to identify a target feature of a letter T among distractor letters (also Ts, in similar colours) and indicate whether the orientation was upright or inverted. Subsequently, participants completed a letter Flanker task where the target was presented centrally and a congruent or incongruent distractor presented above or below the target had to be inhibited. It was expected that, if the cognitive capacity reduced that more task irrelevant information would be processed, with higher cognitive load (e.g. the multiple component task condition). However, if the cognitive capacity was increased, in the multiple component task condition should result in reduced interference on the Flanker task, as the more top-down capacity would be available to differentiate between targets and distractors.

Interestingly, my results indicated that - in line with previous research on enhanced perceptual capacity - distractor interference was *reduced* in the autistic sample (suggesting an increased cognitive capacity). More specifically, when the visual discrimination and Flanker task were combined, autistic participants showed reduced interference from the additional distracting item on the Flanker task.

This is an interesting and important finding: decreased interference from a distractor indexes preliminary evidence of an increased cognitive capacity in the autism sample. I.e. when performing two tasks concurrently, autistic participants have spare cognitive capacity to filter out the task irrelevant information – whereas no cognitive control capacity is available for the non-autistic participants to ignore the task irrelevant information as effectively (resulting in increased processing of incongruent information on the Flanker task for the non-autistic sample).

It is however not currently known how an increased cognitive control load would manifest. As the 3-way interaction between group, load and congruency was not significant, it the results could mean, that autistic people showed a reduced distractibility overall on both high and low load conditions and that this modulated similarly to the non-autistic group. Therefore, future research has to be conducted to address individual differences in cognitive control load. Nevertheless, the findings indicate an advantage in the autism group up indicating reduced distractibility.

One suggestion, is that the improved performance observed in the autism group might be related to a preference for a local information. Autistic people have previously shown a preference for processing the local features of objects (e.g. Jolliffe & Baron-Cohen, 1997). As the target letter in my study was presented in a smaller font compared to the incongruent letter, this might have aided performance in the autistic group. However, not much is known about Flanker task performance in adulthood in autistic people, so it may be the case that previous difficulties seen in autistic children on the Flanker task might mature with age.

Whilst the findings in Chapter 2 indicate an intriguing picture of reduced distractibility or improved cognitive control in autism, there are limitations. Firstly, participants were not matched on basic cognitive abilities or IQ measures, as this was difficult to operationalise in the context of the online study (and face-to-face data collection was not possible due to the COVID-19 pandemic). In addition, participants in the autistic group self-reported that they received an autism diagnosis. This was confirmed with an autism trait measure, however a more thorough confirmatory process (e.g. involving a researcher-administered ADOS) was not possible online. With that in mind, the study provides preliminary evidence for an increased cognitive capacity.

Whilst the findings in Chapter 2 indicated an increased cognitive control capacity, the neural mechanism on how the tasks load on cognitive load remains however unclear. Previous research has indicated that sensory cortical areas play an important role in visual spatial attention and visual maintenance. As yet, the capacity limits of perceptual load have largely been unexplored using ERP markers of attention and maintenance in autism. Thus, across the subsequent two chapters I explored visual working memory capacity and perceptual capacity further using electrophysiological and behavioural markers.

An Increased Visual Working Memory Capacity in Autism? The Load Theory literature suggested that visual maintenance load has a similar impact on target detection as perceptual load does (Konstantinou & Lavie, 2013). The aim of Chapter 3 was twofold: 1) to assess whether increases in visual working memory capacity would be seen for autistic people, similar to the enhanced perceptual capacity and 2) to examine filtering efficiency as indexed by the CDA. Thus, I used a standard bilateral visual change detection task that has been frequently tested in the wider literature and clinical groups yet has not been applied in autism. Importantly, in the task two levels of load were presented to the participants, with either two or four target shapes (blue rectangles). In a distractor condition two task relevant shapes and two task irrelevant shapes were presented. In previous work the paradigm has shown to also be a reliable marker of filtering efficiency, people who filter out the two task irrelevant shapes had a reduced CDA amplitude that was similar to the two target condition (Vogel et al., 2005). However, people who were less efficient in filtering out the task irrelevant shapes had a CDA amplitude that was similar to the four target condition.

Importantly, based on previous work on increased perceptual capacity in autism, I predicted that visual working memory capacity would also be increased in autism. In line with the hypothesis, autistic participants showed an increased visual working memory capacity (set size 4) as measured on the CDA, compared to the non-autistic sample that appears to be reaching the capacity limit at set size 2. Importantly, these differences were not present at the behavioural performance level. There were no significant performance differences between the groups and no evidence at the low load or the distractor condition which suggest that there were no differences in filtering efficiency across the groups. As such, whilst evidence in Chapter 3 indicated no behavioural evidence for group differences in filtering irrelevant information, preliminary electrophysiological evidence for an increased visual working memory capacity was found in autism.

These findings can only be taken as preliminary evidence as the sample sizes and the effect sizes in the study were small. In addition, the CDA amplitudes were not correlated with behavioural performance markers of capacity (Pashler’s K). In addition, the paradigm presented in Chapter 3 only tested performance at set sizes 2 and 4, it is therefore unclear whether the asymptote for visual working memory capacity was reached in the autistic group. To replicate the findings presented in Chapter 3 an additional EEG study was conducted in the subsequent Chapter. The set size was presented continuously from set size 2-5, to allow for a better understanding of capacity limits. An additional paradigm was also added to assess perceptual capacity using a subitizing task to contrast performance across the two measures, to better understand perceptual capacity limits.

Contrasting Visual Working Memory and Subitizing Capacity. Subitizing has been suggested to be a marker of perceptual capacity (Eayrs & Lavie, 2018). Therefore, in Chapter 4, two qualitatively similar paradigms were used to assess visual working memory capacity and subitizing capacity, in order to elucidate any links between the two capacities for autistic people. Two lateralised paradigms were used. The subitizing paradigm contained 2-6 target items that flashed up and participants had to indicate how many items they saw by entering the number using the keyboard. In the change detection task, 2-5 target shapes were presented and participants had to memorise the array. After a short delay they were presented with a second array and were asked whether the array changed or not.

Interestingly, there were no behavioural differences between the groups and the ERP findings indicated that autistic and non-autistic participants did not differ in visual working memory capacity as measured on the CDA. Electrophysiological group differences were however reported on the N2pc in the subitizing task, suggesting a reduced amplitude in the autism group that is indicative of a reduced subitizing capacity.

While it has been theorised that perceptual and visual working memory capacity may reflect a common shared resource (e.g. Konstantinou & Lavie, 2013), the finding of a dissociation may suggest that the magnitude of autism's effects on capacity are larger in the perceptual domain. This suggests some caution in the theoretical emphasis of a shared capacity in perceptual attention and visual working memory, as these two constructs do not appear to be entirely overlapping in autism. Importantly, there were limitations, as the study

Feasibility of an Online Meditation Training Study. In Chapter 5, to ameliorate difficulties experienced by autistic adults such as increased levels of distractibility as a result of altered attentional behaviours an intervention study was conducted. In recent literature on attentional training evidence has emerged suggesting that selective attention can be trained through cognitive training paradigms and mediation. Therefore, in Chapter 5 I assessed the feasibility of a neurofeedback mindfulness intervention for autistic adults. In addition, I assessed whether meditation training could improve aspects of executive functions and mental health. Participants were randomly assigned to either receiving a smartphone app-based meditation (active control group) or a neurofeedback guided meditation (experimental group). The neurofeedback device used on the experimental group has integrated EEG sensors and connects via Bluetooth to the smartphone. An algorithm that is based on EEG frequency bands associated with meditative states translates the neurofeedback into auditory feedback. The soundscapes that the participants can select gives feedback based on the levels of attention, such as stormy weather as a cue for distraction and calm weather sounds when attention is refocused on the meditation practice. In the active control group, the same smartphone application was used, in which participants listened to their preferred soundscape that played the sounds at random. The meditation training lasted 14 days and participants completed 10 minutes of meditation each day (a minimum of 100 minutes was required to be eligible to further participate in the study. Pre- and post the meditation intervention participants completed self-report questionnaires and experimental tasks, in which they detailed their attitude and previous experience of meditation and after the training using open ended questions. In addition, participants reported their self-reported mental health scores and completed three experimental tasks, Flanker task, a Corsi-block tapping and a task switching task.

The feasibility was assessed using compliance rates and open ended-questions prior and after the training to understand people’s experiences of mediation. The compliance rate was relatively high, however, a mixed picture emerged for the qualitative data, suggesting that some participants found the intervention useful and it brought them improved aspects of mental health, sleep, focus and a routine. However, other participants reported that the meditation programme had negative experiences partly due to a perception of the training as a chore, feeling that meditation was different to what they had anticipated, and some participants felt that meditation had adverse effects and felt that meditation made their typically constantly occupied cognitive processes feel too quiet. Other technological and sensory challenges were also discussed. Whilst no improvement for executive functions were found, participants self-reported mental health score improved. Importantly, other participants reported that they did not benefit from the meditation training and the meditation training made some of their cognitive symptoms worse. This suggests that the meditation training is not a feasible training for all autistic people. Interestingly no differences were found for executive function tasks. However, on average self-reported depression, stress and anxiety decreased as part of the meditation training for both groups. The importance of a mixed methods approach in intervention research and the implications of the findings and how voices of autistic people should be heard when developing intervention trials will be further discussed in the present chapter. However, I will firstly focus on the findings on this thesis more broadly and discuss how the present findings can be reconciled with the previous literature and discuss the implication of the practical implications of the findings.

How can we reconcile the mixed picture of capacity limits in autism with the previous literature?

Chapter 1 detailed a mixed picture of cognitive control abilities, maintaining and setting priorities and filtering information for autistic people. Similarly, this mixed picture of performance differences emerged across the empirical Chapters 2, 3 and 4 regarding attentional mechanisms, saturation, and filtering abilities. In the introduction to this thesis, I discussed different hypotheses that have emerged in the autism literature and could account for the mixed findings in selective attention abilities for autistic people. The hypotheses made different predictions, postulating that autistic people have 1)a too narrow attention spotlight, 2) overly broad attention that results from an inefficient filter, 3) over selection of features that share similar properties (top-down modulation) and 4) enhanced perceptual/cognitive capacity using the framework of Load Theory (and the relationship to the sensory recruitment hypothesis). Each of the proposed hypotheses will now be discussed in relationship to the empirical chapters and the wider autism literature.

A too narrow attention spotlight, was hypothesised to lead to an over selectivity of a small proportion of task features of a more complex task, leading to a focused attention spotlight (Lovaas et al., 1979). The underlying mechanism for the over selectivity is currently still unclear; a sensory overload or the attentional spotlight was thought to be closely related to findings predicted by the weak central coherence theory (Ploog, 2010). Whilst there was no relationship between sensory sensitivity and aspects of attention across this thesis, elements of a local presentation have aided the performance in the autism group in the empirical study presented in Chapter 2. The proximity of the neighbouring presentation of the incongruent Flanker letter presented in a capital font might have autistic participants' performance through a local processing preference seen in autism (F. Happé & Frith, 2006b). It was however not directly predicted in the hypothesis that when information presented next to each other a smaller target presentation could aid performance. Otherwise, performance advantages would be expected to result in improved performance in standard Flanker tasks as well when autistic people select information with a too narrow attention lens. No evidence for a narrow attentional spotlight was however reported in Chapter 3 or 4 using behavioural or ERP evidence.

In the autism literature, further empirical support for the attention spotlight hypothesis came from Townsend et al's. (1996) study in which participants had to detect and discriminate the spatial targets across two different experimental tasks. Moreover, Townsend et al. (1996) tested autistic and non-autistic participants (age range 16-37 years) and found that the orientation of attention to the targets was delayed in the autistic participants. This was taken as evidence for narrow attention style, especially because attention orientation was facilitated in trials where a spatial cue indicated the position of the target and helped participants to orient their attention to the target location. This suggesting that a pre-stimulus cue aids orienting of the spotlight.

Interestingly, the findings of the pre-cue might help to explain performance difference on the change detection task presented in chapters 3 -4. Visual working memory capacity was larger in the task that used visual spatial cues towards the target hemisphere, compared to the task where no pre-cue to the target side was presented for the autistic participants. Whilst it is plausible that the spatial cue could have facilitated performance, it is unclear whether the findings could be related to a too narrow attention spotlight. The target objects were presented lateralised in one visual field and not locally presented in one spotlight. If the attention spotlight was shifted to the visual side, this would lead to an over selection of all information, including distractors and decreased filtering efficiency would be observed. However, no group differences for filtering inefficiency were observed of task irrelevant information in Chapter 3. Nonetheless, the facilitation of performance with using spatial and target cues, likely unrelated to the attention spotlight hypothesis, should be explore in further research. In addition, the findings however of a reduced narrow attention spotlight are difficult to reconcile with improved visual search performance in autism and findings of improved detection of information presented in the periphery (Remington et al., 2012). Before investigating the role of perceptual and cognitive capacity, I will explore the role of filtering efficiency and top down facilitation in autism.

Contrary to the attention spotlight hypothesis, in which the attentional focus was thought to be too narrow (Lovaas et al., 1979), an alternative hypothesis was postulated, suggesting an overly broad attentional focus (J. A. Burack, 1994). Thus, the filter to distinguish between targets and distractors was thought to be inefficient in autism (J. A. Burack, 1994). More recently, findings from EEG research has produced support for the hypothesis. For instance, Milne and colleagues (2013) conducted a visual search experiment in adults with high and low autistic traits. Interestingly, the participants with high levels of autistic traits were better at visual search and showed a reduced P3b amplitude, which is associated with improved visual search but was also associated with reduced attentional filtering. Similarly, (J. W. Murphy et al., 2014b) tested autistic adolescents on a cued inter-sensory (audio-visual) attention task. The autistic participants showed a reduced preparatory alpha band modulation and reduced suppression of task irrelevant information. The target detection across conditions when two modalities were involved was also reduced. Together the findings indicate a modulated electrophysiological activation with regards to distractor processing in autism which might be taken as evidence for an inefficient filter in autism. Interestingly, in the present thesis, there was no direct evidence for an inefficient filter for task irrelevant information as indexed by the CDA (Chapter 3). However, when visually inspecting the change detection task in Chapter 4, a clear N2pc emerged in the early time window that suggests an early saturation of attention, which might suggest that autistic people might have selected more information than required at earlier set sizes. Interestingly, the opposing evidence was found in behavioural studies using the multiple component visual working memory Flanker task (Chapter 2) suggests improved filtering abilities as autistic participants seem to be more efficient at filtering out the task irrelevant information. Therefore, the findings in this thesis indicate a mixed picture when it comes to filtering information, there was no direct empirical evidence using behavioural and ERP markers for filtering inefficiency in autism. Further research needs to be conducted to understand the conditions under which autistic people might be more/less efficient in filtering task irrelevant information. A non-lateralised task might also help to understand under what circumstances autistic people process task relevant and irrelevant information.

It was previously postulated that altered top-down attention could result in altered attentional processes in autism. As previously highlighted, attention can be divided into top-down and bottom-up processing. When attention is goal driven (top down, e.g. searching for someone with a red jacket in a crowd of people) and exogenous attention when attention is oriented towards external events in the environment (e.g. seeing a sudden movement of someone in a crowd, bottom up; Posner & Petersen, 1990). In the autism literature, top-down and bottom-up attentional processes were thought to be modulated (e.g. Keehn et al., 2017), leading to activation of non-targets that shared similar features more often than in other tasks. As such, when a target consists of a certain colour, other distracting information would be processed if they share the same defining features of the target (relying on top-down processing e.g. Folk & Remington, 1998). If attention capture of shared task features is increased, this would be taken as evidence for increased top-down influence. In the context of the load theory, top-down attention is required to maintain stimulus priorities (e.g. which target is relevant). In Chapter 2, the findings indicate that autistic people exhibit improved top-down control compared to the non-autistic sample, as the target priorities are maintained on both the visual discrimination task and the Flanker task. Likewise, on the change detection task, in Chapter 3 there is preliminary evidence for improved top-down attentional control. The finding however was not replicated in Chapter 4. It is therefore currently unclear what enables improved top-down control in autism. Interestingly, the observed findings of a reduced subitizing capacity, might be related to increase bottom-up processing, as it might be that additional task. As yet, the role of top-down and bottom-up processing is still unclear. For instance, theoretical work of a Bayesian theory suggests that autistic people rely more on bottom-up processing rather than include previous knowledge (Pellicano & Burr, 2012).

Lastly, as previously discussed, the Load Theory predicts that at any given time, we automatically use all our perceptual capacity to process information in an automatic and mandatory way, and our cognitive control processes are used to influence what information is prioritised and minimises intrusions of irrelevant information. Importantly, Load Theory proposes a dissociation between distractor processing in situations of high perceptual and cognitive load. When a task exhausts our perceptual capacity because it contains a great deal of potentially task-relevant information (high perceptual load), we stop processing task irrelevant information. Conversely, on a task that requires high cognitive load (i.e. involves multiple demands such as memorising a digit string while performing a visual search task) the ability to prioritise targets and block out distractors is diminished, and increased distractor processing is observed.

The underlying mechanism for perceptual processes in the load theory are thought to align with the sensory recruitment hypothesis (Konstantinou & Lavie, 2013). The account suggests that maintenance of visual information for visual features is realised in the same visual cortical region that is involved in the initial perception (D'Esposito & Postle, 2015; Serences et al., 2009), the region that is recruited for the visual perceptual processes. The sensory recruitment hypothesis suggests that the prefrontal cortex provides top-down signals for goal relevant maintaining and prioritising of visual information across the posterior region (Serences et al., 2009). In the present thesis, I showed evidence for a visual cortical involvement in perceptual and visual maintenance processes as indexed by the CDA and N2pc markers. Importantly, whilst there was evidence that the autistic people's performance was improved or similar to the non-autistic sample, the capacity limit (indexed by the N2pc) of the autistic participants was reduced on the subitizing task compared to the non-autistic sample. This suggests a dissociation in sensory recruitment for the autistic sample and that the sensory recruitment network might be modulated in autism.

Importantly, the preliminary evidence found for an increased cognitive control capacity in Chapter 2, indicates that the ability to maintain task priorities (ignore incongruent information in the Flanker task) was improved under high levels of cognitive load in the autism group compared to the non-autistic sample, indicating an increased capacity for cognitive control. This could have important real-life implications that will be further discussed in the next section of this chapter.

Practical Implications for an increased cognitive control capacity in autism.

Although the underlying mechanisms for attentional processes in autism are still currently unclear, the findings discussed in the previous section indicate that there are visual perceptual strengths in autism. In this section I will explore how visual perceptual process can be supported and the implications for everyday life.

Interestingly, the findings of an increased cognitive control capacity (or reduced distractibility) in autism presented in Chapter 2 are in line with anecdotal and qualitative evidence of an increased hyperfocus in autism. Hyperfocus is a state in which one fully concentrates and absorbs in the task and external or unrelated stimuli are ignored (Ashinoff & Abu-Akel, 2021). For instance, in a recent qualitative study, 28 semi-structured interviews were conducted with autistic adults and the improved ability to focus was one of the key themes that emerged in the study, with participants anecdotally highlighting the states of hyperfocus as one of their core strength (Russell et al., 2019). Likewise, hyperfocus has been described by McDonnel and Damian Milton (McDonnell & Milton, 2014) an autistic scholar as the state of focus as a flow state in which one can fully engage with the task and provides a source of predictability and controllable environment. Hyperfocus was also thought to be related to the preoccupation of parts of objects (a prior DSM-4 category,(APA, 2000b) and “Difficulty in shifting attention, disengaging attention from details” (Geurts et al., 2009, p. 75). Interestingly, in line with Geurts and colleagues' (2009) suggestion the findings of the present study indicate that there might be task related factors that could help to achieve improved hyperfocus or cognitive control by orienting the task feature towards local processing of information. This has important real-life implications, the organisation of the stimuli of tasks might be crucial. For instance, as indicated in the present study, adjusting standardised task such as Flanker to allow for processing of local information might therefore harness attention capture more efficiently and lead to improved performance in the autism group. Therefore, framing questions and information differently to adjust to the strength of autistic people might help to facilitate attention. This could have important real-life implications for the classroom, workplace and on therapeutic interventions.

For example, one direct application of the present work might be related to standardised tasks used in the candidate selection process. Sadly, employment rates are lowest for autistic adults compared to any other disability group, with only 22% of autistic people in employment (either full-time, part-time, or temporary work) in 2020 in the UK (Office for National Statistics, 2021). Amongst other barriers to employment (e.g. Lorenz et al., 2016), standardised cognitive pre-employment assessments are commonly used to test candidates and could create difficulties for autistic people. These psychometric aptitude tests aspects of verbal, numerical and abstract reasoning. Whilst autistic people might have difficulties completing aspects of these tasks, it might be that these standardised measures are biased against autistic people based on the presentation of the visual information. As findings from this thesis indicates, aspects of cognitive performance can be harnessed by presenting information more locally or providing visual cues. Therefore, more needs to be done to help facilitate the attentional processes in autism and create strength-based assessments tools that might facilitate the recruitment and reduce the bias against autistic people's attentional mechanism.

In addition to structuring tasks and in favour of local processing, the findings of the present thesis also indicate that, at least in certain situations, autistic people do not have any difficulties maintaining visual information. In fact, their performance might even be improved. However, when subitizing information in everyday, autistic people might use different strategies or might count objects. This can for instance be counting the numbers of apples in a fruit ball rather than subitizing it. More applied research is needed in the field to directly identify how aspects of attention can be improved by the adjusting the stimulus organisation.

Indeed, not much is known about the practical focus on the organisation of the visual environment that could aid attention in autism. For instance, the National Autistic Society lists generic advice and strategies such as colour coding of information and practical applications on time-management (National Autistic Society, 2020) , however no suggestions with regards to how visual information can be structured to harness aspects of attention in autism are indicated. A recent study has investigated perceptual capacity in autism in a virtual classroom, where the board behind the teacher who was either kept blank, had irrelevant visual information or task relevant visual information on it. Importantly, the study indicated that autistic children compared to non-autistic children benefit from task related information to fill their increased capacity, but also process the task irrelevant information whilst still maintaining the content of the teacher's lesson (Remington et al., 2019). Crucially, more research is needed to investigate more applied real-life scenarios to allow for better learning outcomes and recommendations for teachers.

Voice of Autistic People in Developing Interventions/support services.

In recent years, a wealth of research on interventions in autism has emerged in the cognitive training and mental health literature. However, the autistic voice is often overlooked, for instance a recent review by Scionti and colleagues (2020) investigated the cognitive training effects on executive functions in autistic children. The review did not indicate that a single study analysed the direct experiences of autistic participants when taking part in the intervention. The findings from Chapter 5 indicated that giving autistic participants the opportunity to feedback their experiences is invaluable when developing interventions. The evidence that some autistic people had adverse experiences and without the mixed methods approach would have been missed. Therefore, allowing participants a voice in the research process is a powerful tool to produce the best possible outcome for autistic participants. Especially, as the previous literature indicate that adverse events might occur in cognitive or meditative training (e.g. Farias et al., 2020). Therefore by involving community members, and give autistic people to express their experiences directly, allows to understand experiences that would be routinely missed in the research process (Bracic, 2018). Whilst investigating the experiences is important, a co-produced approach to interventions should however be the gold standard.

The James Lind Alliance in collaboration with the autism charity Autistica has highlighted research priorities in autism conducting a priority setting exercise in the UK and a large survey with over 1000 respondents. The top research priority highlighted by the community indicated that finding interventions to improve mental health is crucial. It is therefore vital to investigate and test the feasibility of interventions to improve mental health in autism. Evidence-based interventions that listen to the voice of autistic people are often lacking. Only more recently, participatory, co-produced work in autism literature emerged (e.g. Benevides et al., 2020; Sue Fletcher-Watson et al., 2019). Interestingly, Benevides and colleagues (2020) conducted a co-produced priority setting exercise for mental health research that indicated that a self-managed intervention to improve aspects of mental health were listed as the number one priority. As such the participants voiced that they prefer to have a tool that they can use without a gatekeeper such as a therapist. However, not many evidence-based, co-produced tools are currently available and as the meditation intervention indicates it is crucial to listen to people's needs to better understand the experiences of autistic people.

Importantly, feasibility whilst the quantitative findings presented in Chapter 5 suggests that on average autistic people's mental health improved in both meditation intervention groups, the qualitative findings are mixed and highlight that listening to the voices of autistic people when developing interventions is crucial. As it transpired from the results in the intervention study, often one intervention approach might not fit all participants. Therefore, co-produced pragmatic trials, by offering participants alternative intervention programmes that they can chose from rather than randomly allocate to an intervention, might help to improve outcomes and map the interventions onto the participants' strength and interests.

Future studies

In addition to the recommendations for future research mentioned throughout this thesis, there are a number of potential avenues that could be explored to further our knowledge about visual perceptual processes and attention in autism.

Firstly, the findings presented in the thesis have only looked at aspects of *visual* processing. Interestingly, similar findings of enhanced perceptual capacity were found when tested on auditory domains (A. Remington & Fairnie, 2017). Similarly, to the visual selective attention ability literature, multi-modal processing was shown to yield mixed findings in autism. For instance, Tillmann and Swettenham (2017) found that autistic people showed improved multi-sensory facilitation when presented with visual and auditory information simultaneously, however other studies found a reduced multisensory facilitation on a visual search task across the same sensory domains (Collignon et al., 2013; Lovaas et al., 1979; J. W. Murphy et al., 2014b). A recent study that investigated the shift across visual, tactile and auditory modalities and found no reaction time differences when switching between modalities for the autistic and non-autistic participants (Poole et al., 2021). The authors applied a drift diffusion model that takes into account the underlying cognitive processes in accuracy and reaction time and is a measure of the quality of the information extracted from the array. A reduced drift rates suggest more efficient processing and the study revealed that autistic participants showed reduced drift rates suggesting a higher quality of information processing. One hypothesis was that autistic participants' cross-modal processing might be less influenced by attentional networks and that modalities are treated more alike. This provides an interesting avenue for future research. Interestingly, the CDA can also be used to assess tactile visual working memory capacity limits (Katus & Eimer, 2019) therefore, broadening the findings across different modalities and assessing multiple modalities in the same task might help to better understand attentional processes and create more real-life situations.

Secondly, it is important to use real-life stimuli instead of coloured objects and letters as used in the present thesis to better understand the real-life implications of this work. For instance, Xie and Zhang (2018) found that the familiarity of objects (Pokémon characters) was significantly associated with CDA activation and shows that information consolidated in long-term memory might aid performance. Interestingly, a recent study found that when presenting participants with an object that is related to their own personal (circumscribed) interest, this increases attentional facilitation for non-autistic participants but not for autistic participants (Parsons et al., 2017), it is therefore important to explore aspects of attention using real-life stimuli further.

Likewise, in the present thesis only simple objects were used in the experimental paradigms. However, previous research has indicated that autistic people showed superior processing skills on low level perceptual tasks but not on more complex objects (Bertone et al., 2003, 2005). Attention processing remains however unexplored in relation to moving objects in autism, the N2pc and CDA were shown to be modulated by the number of items presented in a multiple object tracking task (Drew & Vogel, 2008; Mazza & Brignani, 2016). It could therefore be an interesting avenue to test capacity limits in multiple object tracking tasks in autism using electrophysiological markers to further advance the understanding of underlying mechanisms of moving objects in autism.

Lastly, another important aspect alluded to throughout this thesis is related to the cognitive heterogeneity in autism. Large scale, multisite studies have emerged in recent years to help understand whether there are emerging cognitive profiles in autism using algorithms (i.e. Loth et al., 2017; Mei et al., 2020). Other methodological approaches such as analysing individual differences in studies with smaller sample sizes might also help to better understand individual differences. Especially, in ERP research the activation of each participant is averaged across trials, which leaves a single data point per participants (across conditions), however other approaches make use of single trial performance and might help to better understand cognition and sustained attention. Whilst there might be underling cortical organisations that might contribute to the heterogeneity of cognitive profiles seen in autism, co-occurring conditions might play an important role in aspects attention. Therefore, the throughout the present thesis, self-reported aspects of co-occurring conditions in autism were collected for mental health, sensory processing, and ADHD. Whilst no evidence for a relationship between the self-reported measures and aspects of attention were found, it is important to understand the aspects of attention better in autism. Therefore, future studies should address the aspects of attention more systematically, by comparing performance across groups with and without co-occurring mental health difficulties, ADHD traits and sensory processing difficulties. In addition, in the present study only participants were included who had an IQ over 80. Future studies therefore should test whether aspects of attention are altered for autistic people with more complex needs. It is also currently unclear whether aspects of attention are unique to autism, cross syndrome comparisons with participants with Down Syndrome or William's Syndrome might help to further our understanding with regards to the university and specificity of attention modulation observed in autism.

Concluding remarks

The work presented in this thesis has advanced our understanding on attentional capacities limits in autism. Importantly, the present thesis highlighted that attentional processes in autism are not deficient but modulated with aspects of improved attention. Behavioural and electrophysiological markers of attention showed that an improved (chapter 3) and similar performance (chapter 4) in visual working memory capacity emerged in the autism group compared to non-autistic participants. Importantly, the capacity for a subitizing task that was expected to recruit the same visual processing areas in the sensory cortex indicates that performance was reduced in autistic participants compared to non-autistic participants. This emerging dissociation might suggests that different visual sensory processes are involved in autism or might reflect different strategies when subitizing.

Evidence for cognitive strength emerged with regards to cognitive control capacity in autism (chapter 2). The findings of this work raises implications for how the observed strength can be harnessed in daily life, for instance by adjusting the visual presentation of tasks and rethinking the organisation of standardised tasks, that might disadvantage autistic people proportionately more.

Finally, improving our understanding of attentional mechanisms can help to improve access to education, workplaces and services. Therefore, the practical application of an intervention study was assessed. The findings of an online meditation training programme indicates that the meditation training was only suited for some participants. The intervention programme highlights that a mixed methods approach is fundamentally important to understand the experience and develop suitable programmes for autistic people.

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Appendices

Appendix A

Table 11. llustrative quotes on the content analysis on barriers towards meditation

Categories	Codes	Frequency	Written excerpts of participants on their previous meditation experience
Scepticism towards meditation			
	Scientifically unfounded		I have a pretty neutral attitude to meditation itself, but I worry about the ways it is being framed as a solution to mental health problems in the absence of proper funding of mental health care. It seems like it is being used as a tool in the neoliberal agenda of self-responsibilization that ultimately justifies the rolling back of the welfare state. H3 I think it's a bit gimmicky and 'hippyish'. C5
	Illogical and abstract nature of instructions		I have tried to meditate a couple of times, but I didn't really understand the point of it and found it hard to do. I have also participated--unwillingly--in a 'mindfulness' workshop in which we were told to listen to our breathing and relax. (H2) I am quite sceptical of mediation or mindfulness having any positive impact as it seems to abstract and impossible. C1 Honestly I'm not too sure what it involves. I was given a relaxation tape by a paediatrician when I was maybe about 10 and I thought it was a bit illogical as it talked of legs getting heavy and weighed down etc and they were the same as they were before. However I would like to retry it and see if it does work. H8
Inability to focus			
	Uncomfortable focus on breath		I don't particularly want to listen to my breathing. H2

		Focus on breathing makes it worse. H17
		And I worry about focusing on my breathing too much in case I breathe too fast or forget how I'm supposed to breathe. H22
	Routine	found it very boring and failed to keep it up after a very short time H18
		I am terrible at consistently implementing new routines e.g. I have never managed to make toothbrushing a regular part of my routine, I understand the need for dental hygiene, I just can’t regularly do it. H4
		However I do find I do not get the time or I forget. C16
		Did think about trying some years ago, but 20mins twice a day seemed an impossible commitment. C19
	Mental Chatter and concentration	I just spent the time thinking through various projects and deadlines. H2
		Hard to concentrate and focus on it. Get distracted with intrusive thoughts. Or things I have to do or pressure I am under. H9
		I have tried to meditate in the past but found I was distracted very easily, it was hard to sit still and I couldn’t focus. H13
		Concentrating on it was too difficult. C11
		Have tried to do mindfulness but get distracted very quickly unless it's guided. Sometimes I feel that my mind is running too fast to slow down to meditate. C12

		Have tried but mind wonders.H17
		I don’t think I could sit still and focus in that kind of way. I can’t turn my brain off. H20
		I found it difficult to concentrate on. H22
		Many years ago I tried it, but didn't get it as I just sat there thinking about things to do or going over things that had happened. H25
		My mind races 110% of the time. I would welcome a break from my own thoughts C19
Distracting environment		
	Social distraction	Don’t want to do it if I have to be in a room with a lot of other people. Anxiety. H4
		But I have never had the chance to part take as there would be too many people there. Also they would annoy me and I would be easily put off. C10
	Hyperawareness of soundscape of class/app	I have struggled to find a voice that I am happy to listen to with thinking of the way they pronounce certain words. H12
		Tried once in past following a body scan meditation but just didn't engage, found the person's voice annoying. If the sound bugs me then I won't be able to engage in it, and sitting in silence and trying myself wouldn't work either. H14
		I always struggled to keep concentration with the noises in the venue and the movements of others H27

Appendix B

Table 12. Illustrative quotes of the themes and subthemes for the thematic analysis

Theme and subtheme	Written excerpts Headset Group	Written excerpts Control Group
Challenging Process		
Exacerbating autistic symptoms	"I don't want to just focus on one thing when I have several exercises, debates, planning discussions and pattern-noticing activities going on in my head most of the time. I like the activity in my head, especially now that I am happier about having it and less concerned that it is a problem (which is a product of adjusting to, accepting and beginning to value the diagnosis). It feels like meditation is meant for non-autistic people who might want to empty their brains and focus on their sensations." H2	"My autistic ability to hyperfocus meant that focussing on my breathing resulted in over-breathing, which made me feel physically and mentally ill. This experience only reinforced my belief that "mindful" meditation is absolutely unsuitable for me and I will never attempt to practice it again." C9 “I didn't enjoy trying to meditate. If anything, trying and failing to maintain focus on breathing caused more stress. I think that forcing my brain to think of anything besides what it was naturally inclined to think about caused similar stress to when my routine is interrupted or I'm disturbed when trying to complete a task. In the last four days, I made very little attempt to focus on breathing because it became counter-intuitive. I did not notice any change to my physical, social, relationship, emotional or thinking skills.” C11 "I felt it spoiled my ability to think and respond quickly. Perhaps my anxious,

		stressed, hyperactive, over-thinking brain is exactly what is needed for good performance in the tests." C19 “I don't seem to be as agile in my thoughts. My thinking seems 'muddy' & I can't remember things I ought to know. I spent a scary half-hour trying to recall the name of the Primeminister! I was determined to remember and not look it up. (I did remember). I wonder if overthinking/my brain going very fast, is better than the calm that meditation brings. I have less to say in conversation as it normally takes me a long time to construct what I'm going to say. Now it seems to take even longer as there is less/no inner voice giving examples of sentences I might say in response to the other person. So I am perhaps less talkative than I was. I'm not sure if I want to be like this. I can imagine that if it is a spiritual thing then it might be seen a good to keep silent, but I feel a bit dumbed down. I rely on my inner voice as a preparation space to plan speech and action. It being 'quietened' is a similar feeling to taking […] sleep remedy.” C18
Feels Like a Burden	“During the meditation practice, I found sitting still very hard and to make myself focus on the meditation” H1	“I noticed that I felt very anxious, impatient and annoyed when doing the meditation.[…] I was not looking forward

“I found the meditation difficult to do, and a bit of a distraction. It became a chore, really. I don't really want to listen to my breathing or 'go with the flow'” H2

“If anything it made me more distressed at points, as I found the idea of controlling the weather with my brain waves to be extremely stressful (like I had responsibility for it, and the pressure was too much). I also became overly obsessed with the metrics (comparing my results to previous days).” H3

“[…]however it was hard to make myself actually do it every single day [..] the physical act of listening to my breath was very, very hard.” H7

“I would have preferred 2x 5minutes as I struggle to relax for the whole 10 minutes” H12

“I greatly struggled some days to want to do the meditation, it felt like a chore at times. […]Didn't notice much, found I was happy to end the study as many days did not feel like doing the meditation.” H14

to doing the 10 minutes. I persevered but I do not feel it has had the impact on me that I expected.” C6

“10 minutes without guidance seemed a long time. I also was too stressed for a few sessions so missed them.” C8

“The meditation was spectacularly unhelpful and actually made me feel worse. I hate "mindful" meditation. […] It makes me feel worse, both short-term and long-term” C9

“It made almost no difference and towards the end, I only continued for the sake of taking part in the study. When the notification popped up to tell me to meditate, I procrastinated doing it. My ability to maintain focus on my breathing rather than thoughts got gradually worse throughout the two weeks.” C11

“I've had trouble focussing on the meditation and wonder whether guided meditation would help me more specifically. I think having 10 minutes of silence (background sound) lead more to my brain doing what it wanted, whereas the guided type would be telling me what

	“I found the meditation a bit of a chore” H18	to do. I found it very difficult to remain focussed on my breath, but it might be that I need more practise or that I'm just under an exceptionally heavy emotional load right now.” C12 “Remembering to take part in the programme with the daily time limit (i.e. must do it before midnight each night) was somewhat stressful/another chore in it's own right” C14 “I found it just heightened my awareness of all the little noises round me. I found the pressure of constantly trying to refocus my breathing was more stressful than my normal life. […] I become hyper aware of every tiny itch all over my body so even harder to concentrate. […] I also found myself nodding off a lot, but not in a good way.” C15 “Much better now that I've stopped.” C19
Unmet expectations	“I didn’t really understand what meditating was. I followed the instructions but couldn’t spot any patterns. The sounds of the weather was sometimes calm and sometimes stormy but I couldn’t spot the pattern about what was controlling it. “ H4	“I had hoped that meditation would be a new tool to manage stress and anxiety, but now I'm wary of it” C19

	“I became more aware that it’s something I need to practice and I got too bogged down in not getting the effects I desired with breathing. [The] more I focused on breath, [the] worse it got. Obviously taking in too much oxygen. It’s become something I really believe in though and recognise could be very helpful to continue with.” H17	
Issues with Product	“I was surprised by how much of the time my brain was shown to be in a calm state even when I thought I was distracted.” H1 ”[…]sense of touch from the head set.” H6 “though oddly enough, once I got upset during a meditation and started crying and it recorded it as being calm” H9 “The soundscapes were hugely important in my experience: some really prevented me from getting calm.” H11 “Also felt that muse would have birds if I stopped my breath which seems counterintuitive. The session about posture telling you to sit up, I find meditation much easier being able to lean against a wall or lying down. Or was very fustrating when muse wouldn't connect to the app.” H14	“I tired hard to focus on it and do my best not to hear the sound that found annoying [..]also the fact [you] cannot change the voice of the person speaking” C11 “I tried using headphones, but found the noise track had another layer (the noise was natural - the sea I think, but there was a rhythmic sound under that - no idea what it was, but so distracting I couldn't use headphones).” C15

“I mostly enjoyed the meditation practice (depending on what soundscape I chose). The muse headband is not that comfortable to wear though.” H15

“Also different soundscapes had different levels of calming.” H17

“The sound effected how relaxing I found it. The beach and rainforest were most effective.” H19

“There have been no tangible changes. The muse app and EEG were good, although the soundscapes need tweaking.” H20

“I found the Muse Headband and the 'weather' effect was changing with my breath so it was actually distracting from practice, and the transitions between sounds was sometimes not very well presented with the audio so this could use some calibration and polish. I had hoped this would improve with longer use but it did not improve over the 14 sessions, it did not seem to pick up when my mind was calm and focused. […]I think starting meditation at 10 minute sessions with only initial guidance is quite tough, rather than having more fully guided and shorter

	sessions initially moving into more independent practice. Whilst the headband is quite novel it does make it less practical as a long term solution because it is a bit bulky, expensive and delicate to carry around. Something that synced with heart rate monitoring or blood oxygen levels of fitness trackers would be more practical.” H27	
Importance of calm mind-set	“There were a couple of sessions where I was already more relaxed and the meditation worked better then.” H2 “Sometimes, my emotional states made it hard to keep calm, but even then meditation helped me to relax.” H11	“I often fell asleep during the meditation if I wasn't feeling anxious by it” C6 “Seems like it might only be useful when you can be calm enough to try.” C8
A Welcome Addition to Daily Life		
Interoceptive awareness	“I've found the focus on breathing helpful and sometimes can then work out if its a physical sensation that is wrong e.g. I'm hungry rather than just feeling of panic. I'm a bit better at focusing on one thing at a time. Concentration maybe slightly improved.” H8 “I have thought about my breathing more when I’m getting stressed and overwhelmed.” H12	“I noticed I could more easily think about my body and be aware of it. I also noticed I was more able to figure out what was wrong with my body, rather than just noticing it. For example, if my body felt bad, I was more easily able to work out of that pain was hunger, tiredness, illness, etc” C2 “Also found myself slowing my breathing down when I was getting too panicked.” C8”

	“I feel pretty restful and found I have paid more attention to my breath now” H26	
Mental Wellness	“my mind has been clearer than before and I have not been as anxious […]I have been able to fall asleep quicker than usual and my sleep has been uninterrupted.” H7 “I feel a bit more positive […] Often immediately after the ten minutes I felt more motivated. I've found I've had more fresh air and often it helps me almost reset to then get on with the rest of the day. I've also interesting taken less painkillers. I still get anxious too much but I wonder if I kept this up if this would lessen with time. Others have noticed a slight change for the better” H8 “[..] like to continue with the practice as it brought me a lot of peace, joy and calm and I definitely slept better. It also gave me a bedtime routine. I also noticed that 'my' cat sought me out and curled up next to me during practice!” H9 “Meditation has helped me to remain focused even during busy days, giving me a time when I could do 'nothing', another challenge for me. Overall, it has made me quieter and more relaxed. […]I feel in a good shape, and explaining I meditate has	“I noticed in helped me fall asleep a lot faster because I did the meditation straight before bed, although the quality of the sleep was about the same as before. I've also noticed that it helped regulate my sleep pattern (without an alarm I will still mostly wake up after 9 hours) and that since I stopped the meditation I've woken up once every night for ten minutes at just before 5am before going back to sleep.” C2 “I feel very good mentally, probably better than before.” C4 “feeling of wellbeing […] general positive feeling” C8 “Less tired during the day than before […].” C13 “though I did feel that it benefited me sleeping. In the last week(ish) I did it right before bed and once I was in this routine, it was far less of a chore and caused me less worry/stress.” C14

helped me to do social chit-chat with people.” H11

“I have done it mainly in an evening which has found to be really helpful calming down and relaxing” H12

“Felt a lot calmer, clearer in my mind, reduced incidences of being overwhelmed or hopeless, got a lot more done. Have enjoyed playing card games with my daughter which I would not have had the energy to do before.[..] Emotionally I have felt calmer, increased clarity and able to focus and prioritise the last couple of weeks. I have dealt with stressful events better and have had less incidences of overload.” H15

“i felt better and relaxed in myself [..]” H16

“I have felt slightly more relaxed, only about 1%. And slightly more willing.” H20

“I found that when I was meditating daily that I felt calmer […]. I had a general feeling of well-being that enabled me to focus on what I was doing. […]This in turn enabled me to be calmer in my relationships with others and my partner. I

	would say that it elevated my mood during this time.” H23	
Improved Sleep	“I have been able to fall asleep quicker than usual and my sleep has been uninterrupted.” H7 “I definitely slept better. It also gave me a bedtime routine.” H9 “slept better whilst doing the meditation but once stopped i felt back to how was previously” H16 “It sends me to sleep better.” H19 “I think my sleep and more physical manifestations of anxiety improved over the programme” H27	“I noticed in helped me fall asleep a lot faster because I did the meditation straight before bed, although the quality of the sleep was about the same as before. I've also noticed that it helped regulate my sleep pattern (without an alarm I will still mostly wake up after 9 hours) and that since I stopped the meditation I've woken up once every night for ten minutes at just before 5am before going back to sleep.” C2 “though I did feel that it benefited me sleeping. In the last week(ish) I did it right before bed and once I was in this routine, it was far less of a chore and caused me less worry/stress.” C14
Enhanced Focus	“my mind has been clearer than before” H7 “Meditation has helped me to remain focused even during busy days, giving me a time when I could do 'nothing', another challenge for me.” H11	“it may have helped my focus somewhat” C6 “General boost in attention span” C8 “Seem to be slightly more focused.” C13

	“Felt a lot calmer, clearer in my mind, reduced incidences of being overwhelmed or hopeless, got a lot more done. Increased clarity and able to focus and prioritise the last couple of weeks” H15 “was able to concentrate better. Enabled me to focus on what I was doing.” H23	
A moment of calm	“I did notice that I liked the 'excuse' it gave me to remove myself from everything for 10 minutes every day.” H5 “I found I looked forward to it each day as it gave me ten minutes of calm.” H8 “I felt I could meditate and focus on my breath in a non-threatening way. I loved the feedback system and the way the app was set up. Normally programmes like that just annoy me, but this one was really appropriate and felt right. I feel the fact I am mentally unwell right now has nothing to do with the meditation, in fact, I feel it helped me. I looked forward to my session every evening” H9 “I felt better for taking that 10 minutes a day to focus.” H15	“I enjoyed taking part in the daily meditation.” C1 “Knowing I had 10 minutes of "just be" time coming up did make me feel more calm” C6 “It was nice to have a task to do each day.” C13 “[…]I think I got better at the actual meditation as time went on […]” C14 “how to appreciate quietness more” C16 “I liked listening to the rain.” C17

“i enjoyed the regular calming routine” H16

“I was surprised just how much setting aside time for and doing a formal practice could influence my states of being.” H21

“I really enjoyed the meditation for 14 days. It was good having the motivation of the study to push me to do it each day and I did gain noticeable benefits to my mood and my ability to concentrate during this time” H22

“I have felt able to find time to slow down and relax so will continue was best I can.” H24

“[…] I did like taking part.” H 25