Sensorily Stressed: An Exploration of the Relationship between Anxiety and Sensory Reactivity in Autistic People

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Abstract

Differences in sensory reactivity have been well documented in autistic people of all ages, with differences reported in all modalities, both interoceptive and exteroceptive. Autistic people have also been found to have higher trait anxiety and more diagnoses of anxiety-related disorders. Previous research has identified that more difficulties with sensory reactivity lead to the development of anxiety, with a variety of factors influencing that relationship. However, fewer studies have addressed whether greater anxiety can also lead to more difficulties with sensory reactivity. Four studies are presented in this thesis which address research questions associated with sensory reactivity which, when combined, may additionally offer some insight into the directionality of the anxiety and sensory reactivity relationship.

The first study of this thesis was a co-designed qualitative analysis of autistic accounts of sensory overload, which identified several themes about sensory overload, with implications for the everyday autistic experience. This included the identification of different processing stages with variable capacities and a circular relationship between the likelihood of sensory overload and anxiety. The second study described the construction and validation of a short version of the Glasgow Sensory Questionnaire, which was then used as a compact measure of sensory reactivity. For the third study, a general population sample and a neurodivergent sample were used to assess whether sensory reactivity was present across several neurodivergences, rather than just autism. The results identified that autistic and ADHD traits had a significant overlap, which was also represented in their individual relationships with sensory reactivity. The final study used Virtual Reality to experimentally influence state anxiety and a dual-task paradigm to measure participants' perceptual capacities. This study's results were not as expected, but improvements will be made to the procedure in future work.

Overall, the findings of this thesis point toward anxiety having some effect on autistic peoples' sensory reactivity, alongside sensory reactivity's long-term impact on anxiety. These conclusions offer actionable insights for autistic people and those with influence over the sensory environment.

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1. General Introduction

1.1 Autism

In the psychiatric setting, autism refers to the ‘Autism Spectrum Disorder’ neurodevelopmental disorder diagnosis, which is defined by both the DSM-5-TR and ICD-11 using the ‘dyad of impairments’: deficits of social communication; social interaction; and restricted and repetitive behaviours or interests (APA, 2022; Cashin et al., 2009; World Health Organization, 2019). To receive a diagnosis of Autism Spectrum Disorder from either manual, these features should have been present from early childhood, though not necessarily immediately apparent, and cause significant disruption to daily functioning. Both manuals have room for further characterising specifications, including learning disability, degree of support needs, and presence of other disorders. Autism Spectrum Disorder in its current form has subsumed many previously separate diagnoses such as Autistic Disorder, Asperger’s Disorder, and Pervasive Developmental Disorder – Not Otherwise Specified (Rosen et al., 2021; Volkmar & Reichow, 2013).

Rates of diagnosis of Autism Spectrum Disorder vary considerably across time and place. Estimates of Autism Spectrum Disorder prevalence in a Europe-wide project varied from 0.48% in Southeast France to 3.13% in Iceland (Delobel-Ayoub et al., 2020). Meanwhile, in the United Kingdom, diagnoses of Autism Spectrum Disorder or its equivalent conditions have increased by 787% between 1998 and 2018 (Russell et al., 2022). Given that diagnosis rates have increased most in women, older people, and people with fewer support needs (Russell et al., 2022), it is highly likely that these changes result from more people accessing a diagnosis, rather than changes in the underlying number of autistic people. As the current sex ratio at diagnosis is 3 males to 1 female (Loomes et al., 2017; Sacrey et al., 2017), compared to estimated parity when using a modelling approach (Burrows et al., 2022), this trend will probably continue.

Even when limited to groups diagnosed using these criteria, there is considerable heterogeneity in the lived experience of autistic people. This heterogeneity is present from the earliest developmental stages (S. H. Kim et al., 2016), across all diagnostic criteria (Georgiades et al., 2013), and is likely the result of interactions between genetics, co-occurring conditions, and gender (Masi et al., 2017). As a result, there is considerable variability in the effectiveness of interventions for autistic people in the medical system (Gosling et al., 2022; Siegel & Beaulieu, 2012). These factors, alongside concerns regarding the emphasis on deficits inherent to the medical model and a recognition of the systemic impacts of a neuromajority society, have led autistic advocates to advance a social model of autism within the neurodiversity movement (Kapp et al., 2013). Part of this is the recognition that many autistic people will not have received a diagnosis for the reasons above, as well as barriers within the bureaucratic processes required to do so (Overton et al., 2023). Self-identification is therefore an increasingly recognised alternate means of access to the autistic community and research participation. While imperfect and associated with concerns of validity (Sarrett, 2016), McDonald (2020) found that self-identified autistic people not only responded to questionnaires relating to autism similarly to autistic people with a clinical diagnosis, but also that the proportion of women and older people among the sample were closer to underlying population estimates. For these reasons, it is reasonable to consider the implications of using different potential participant populations.

One area in which the deficit model of autism has been challenged is in language choices. In both the United Kingdom and Australia, many – though not all – autistic people have shown a preference for the use of identity-first language rather than person-first language (Bury et al., 2023; Kenny et al., 2016). This means using terms like 'autistic person' rather than 'person with autism'. This preference results from feelings around autism as a fundamental part of personhood and the stigma that can be implied by person-first language (Botha et al., 2022; Bottema-Beutel et al., 2021). For this reason, identity-first language will be used throughout this thesis.

Autistic people face challenges that greater scientific understanding may help to overcome. Autistic people die earlier than non-autistic people (Catalá-López et al., 2022; Smith DaWalt et al., 2019), have a lower quality of life – with caveats regarding how it is calculated (Ayres et al., 2018; Mason et al., 2022), and face discrimination as a neurominority (Chapman, 2019). In this context, researchers are ethically obligated to consider their position and role in systems perpetuating these inequalities and act to reduce them.

1.2 Autistic Sensory Processing

Differences in sensory processing are often reported in autistic people of all ages in both first-person accounts (Grandin, 1992; A. E. Robertson, 2012; A. E. Robertson & Simmons, 2015) and parental accounts (Dickie et al., 2009). Subsequent research has quantitively confirmed these accounts in adults (Horder et al., 2014; A. E. Robertson & Simmons, 2013; Tavassoli et al., 2014), children (Kirby et al., 2022; Millington et al., 2021), and parental reports (Smees et al., 2023). The consistency of results from these cross-sectional reports and from longitudinal studies (Dwyer et al., 2020; Perez Repetto et al., 2017), imply that these divergences are persistent throughout the lifespan. Differences can be found across all modalities, including the classic senses such as audition (Z. J. Williams et al., 2021), gustation (Boudjarane et al., 2017), olfaction (Tonacci et al., 2017), tactile processing (Mikkelsen et al., 2018), and vision (Simmons et al., 2009) but also lesser considered senses such as proprioception (Blanche et al., 2012), the vestibular sense (Smoot Reinert et al., 2015), and the interoceptive senses (DuBois et al., 2016). Despite their ubiquity, these sensory processing differences are highly variable in their form and valence within and between people.

Some of these differences can be disadvantageous, inhibiting participation in societal common spaces and negatively impacting well-being (B. F. Oakley et al., 2021; A. E. Robertson & Simmons, 2015). However, it is important to note that not all differences are negative. Extensive research has been carried out to explore the superior performance of autistic individuals on low-level perceptual tasks as predicted by the enhanced perceptual functioning theory (Mottron et al., 2001) and the psychophysiological benefits of stimming (Kapp et al., 2019).

1.2.1 Levels of Analysis of Autistic Sensory Processing

There are five different levels of analysis of sensory processing defined by He et al. (2023) where differences between non-autistic and autistic people are explored. The lowest level is sensory-related neural excitability, which considers the response of individual neurons or neuronal networks and is measured using neuroimaging techniques. At this moment in time, research in this area shows high heterogeneity and findings are inconsistent (Schauder & Bennetto, 2016). Current research suggests that previous implementations of the excitation-inhibition imbalance theory may have been overly simplistic (Sohal & Rubenstein, 2019) and there are concerns about the validity of animal models in the neurodevelopmental context (Wilson et al., 2023).

Moving up a level, perceptual sensitivity is an individual's effectiveness at detecting and discriminating between low-level sensory stimuli as explored in psychophysics, though the Sensory Perception Quotient is designed to measure these phenomena using a questionnaire approach (Tavassoli et al., 2014). He et al. (2023) differentiate between sensory-related neural excitability and perceptual sensitivity because changes at either level might not lead to changes at the other. For example, differences of neural sensitivity may not be consistent across stimuli intensities and would, therefore, not affect detection thresholds. Studies at this level find both higher and lower thresholds, sometimes in contrast to predictions (Hadad & Yashar, 2022; Simmons et al., 2009).

Physiological reactivity describes the impact of sensory inputs on the physiological responses of the body, such as the autonomic nervous system or limbic-hypothalamic-pituitary-adrenal axis. Within the autonomic nervous system are the sympathetic and parasympathetic nervous systems which are responsible for the acute stress response and lead to measurable and time-sensitive changes in heart rate, heart rate variability, and pupil dilation (Benarroch, 2014; Lowenstein & Loewenfeld, 1950). In continuation of the theme, experiments using these measures find differences between autistic and non-autistic people, but those differences are variable (Lydon et al., 2016).

Affective reactivity is a person's emotional or cognitive response to a stimulus, such as a subjective judgement of appealingness. While physiological and affective reactivity appear intimately related, He et al. (2023) distinguish between the two because of imperfect coupling between physiological and psychological states given the differing complexities inherent to both (Giannakakis et al., 2022). As it is at this level of analysis that people become consciously aware of their sensory processing, affective reactivity has been well covered by observation and questionnaire-based measures. These include, but are not limited to, the Sensory Profile (Brown & Dunn, 2002; W. Dunn, 1999), Sensory Experience Questionnaire (Ausderau &

Baranek, 2013), Cardiff Anomalous Perceptions Scale (Bell et al., 2006), and Glasgow Sensory Questionnaire (Millington et al., 2021; A. E. Robertson & Simmons, 2013). Most of these questionnaires have variations to cover different developmental stages and languages/cultures. Comparing the Glasgow Sensory Questionnaire, Adult/Adolescent Sensory Profile, and the Cardiff Anomalous Perceptions Scale, Horder et al. (2014) found that they all correlated fairly well with each other and levels of autistic traits, with Pearson's coefficients ranging between .427 and .716.

The final level of the taxonomy proposed by He et al. (2023) is behavioural responsivity, which concerns the observable behavioural response, or lack thereof, to sensory inputs. This level of analysis captures behaviours like those described in the Sensory Profile, such as avoidance or sensory seeking (W. Dunn, 1999). The ease of observability makes behavioural responsivity well suited to the clinical environment (Siper et al., 2017), or where a person is not well placed to articulate their experiences.

The distinctions between the different levels of analysis are important to consider because the language has been evolving (Ward, 2018), which can lead to a lack of specificity in the literature. This is notable in research where direct access to the participant's low-level perception or cognition is limited, such as in children or autistic people with learning disabilities, and researchers must therefore rely upon external observation from clinicians or caregivers, leading to studies using affective reactivity and behavioural responsivity to infer truths about the lower levels (Schulz & Stevenson, 2019). Unfortunately, effects at one level are not necessarily expressed at their adjoining levels (Schulz & Stevenson, 2022). By adopting this analytical model, researchers can offer more complex explanations of the relationships between the levels than simple linear interpretations.

At all levels of sensory processing in autistic people, the hyper- and hypo- prefixes can qualify how a person's sensitivity, reactivity, or responsivity compares to what would be expected from a non-autistic person (Mottron et al., 2001; A. E. Robertson & Simmons, 2013; Takarae & Sweeney, 2017). For example, hyper-sensitive colour perception may allow heightened colour discrimination but sensory overwhelm in colourful environments, while a hypo-responsivity to temperature may lead to someone unnecessarily wearing a coat in the midday summer sun. Most research concerns sensory hyper-reactivity because the negative consequences are self-evident. While hypo-sensitivity is less immediately psychologically distressing, it can still present challenges for an autistic person. For example, hypo-reactivity to pain or the interoceptive senses can lead to autistic people enduring worse injuries or becoming malnourished (DuBois et al., 2016; Moore, 2015).

1.2.2 Models of Autistic Sensory Processing

The varied and inconsistent expression of autistic sensory processing has made the development of explanatory theories challenging; however, several attempts have been made. One area of interest is the distinction between global and local processing (Van Der Hallen et al., 2015). In this model, local processing refers to the processing of individual low-level stimuli, while global processing is used to bring many stimuli into a single percept (Wagemans et al., 2012). Based on this perspective of local and global processing, Uta Frith proposed the weak central coherence theory, which suggests that autistic individuals have difficulty integrating the global context into their percept while maintaining localised processing (Frith & Happé, 1994). This has since been developed, with Happé & Booth (2008) proposing that local and global processing represent two separate but complementary processes. An alternative theory is the enhanced perceptual functioning framework, which posits that rather than autistic people having an inherent dysfunction of their global processing, they instead have a preference for local processing (Mottron et al., 2001). Importantly, this means that an autistic person can still access their global processing to complete a task, but they need to make a conscious decision to do so. Despite the prominence of these frameworks and over 30 years of research, a meta-analysis of studies investigating local and global processing by Van Der Hallen et al. (2015) found no evidence for either enhanced local processing or reduced global processing in autistic people. They argue that the relative ambiguity of the concepts in these frameworks means that researchers have not been consistent when subsequently trying to operationalise them.

A relatively new explanation for autistic perception is the Bayesian or predictive coding model. Bayesian models use a combination of priors – our expectations of what should be – and novel information to arrive at the most likely prediction of reality. As we receive more information, our priors are adjusted to minimise the error of these predictions, which should improve over time. Based on this line of thinking, Pellicano & Burr (2012) suggest that autistic people have weaker priors than non-autistic people and therefore rely more on immediate perception. Conversely, it has also been suggested that autistic people may instead have stronger priors, leading to larger prediction errors when small changes have been made to the environment (Lawson et al., 2014; Sinha et al., 2014; van de Cruys et al., 2014). There is considerable evidence that predictions are affected in autistic people (Cannon et al., 2021), though the nuances of these continue to be explored.

Monotropism is a wider explanation for numerous aspects of the autistic experience, which has implications for sensory processing. Developed by autistic researchers using the lived experience of autistic people, monotropism proposes that highly monotropic people have fewer ‘interests’ at any given time. This leads to their attention being more intensely allocated to those fewer interests and more difficult to reallocate (D. Murray, 2020; D. Murray et al., 2005). Sensory modalities and/or sources can be counted among these interests. Hyper-reactivity therefore results from the sensory information being attended to and hypo-reactivity when it is not. Measures of monotropic and autistic traits are highly correlated, implying that autistic people are much more likely to show monotropic tendencies (Garau et al., 2023). Monotropism remains relatively under-researched, though several key predictions have subsequently been validated (Grotewiel et al., 2023; Rumball et al., 2021).

The last explanation for the differences of sensory processing in autistic people considered here is the impact of sensory capacity (Remington et al., 2009). This theory extends the load theory of selective attention (Lavie et al., 2004). The key principle of load theory is that our perceptual capacity is always fully utilised, regardless of demand. When completing a complex task, the entire capacity is filled with task-relevant information. However, if the task is simple, the perceptual capacity will be filled by task-irrelevant information, which acts as a distraction. The suggestion is that autistic people have an increased perceptual capacity, allowing for good attention to detail in complex environments while also experiencing greater distractibility. There are some concerns regarding the validity of load theory compared to other theories of attention (G. Murphy et al., 2016), though it has been successfully used to predict outcomes in dual-load tasks with autistic people (Remington et al., 2012; Remington & Fairnie, 2017) and has been directly linked to reported sensory sensitivity (Brinkert & Remington, 2020).

The theories addressing the sensory processing of autistic people described here are largely complementary with each other. They all involve the integration of multiple sensory inputs within individual modalities and through combinations of multiple modalities. Both monotropism and perceptual capacity also invoke the use of attention as a selective mechanism for limited processing resources with a large pool of potential information to be processed.

1.3 Anxiety

Anxiety is a mental state characterised by apprehension, avoidance, and cautiousness regarding potential threats, dangers, or negative events (Craske, 1999). This is psychobiologically distinct from fear, which is the response to imminent danger (Grillon, 2008). Anxiety can be a useful response for a person, assisting with uncertain threats and motivating the mitigation or avoidance of future events. Unfortunately, it is possible for anxiety to become maladaptive, especially if excessive or demotivating, leading to a negative impact on mental well-being. Where this persists for some time and with sufficient disruption to daily functioning, a person may be eligible for a diagnosis of an anxiety disorder (APA, 2022).

Anxiety can be separated into two distinct concepts. State anxiety is defined as the response to immediate events and is associated with the activation of the sympathetic and parasympathetic nervous systems (Benarroch, 2014; Spielberger, 1970). Trait anxiety is instead a person's long-term tendency towards anxiety as a reaction to uncertain events or concerns and has long been linked to personality traits (Jorm, 1989; Kotov et al., 2010). The distinction between the two has been demonstrated both psychometrically and neurologically (Endler & Kocovski, 2001; Saviola et al., 2020).

Given the negative effects of anxiety, it is unsurprising that considerable attention has been paid to explaining why different people experience different levels of anxiety in both clinical and non-clinical contexts. For example, it has been shown that anxiety can arise as a learned response to previous negative experiences, such as pain or punishment, and can be triggered by complex, context-dependent stimuli (Boddez et al., 2014). Cognitive approaches tend to concentrate on the relationship between situational appraisals based on cognitive schemas and the emotional and behavioural responses they trigger (Ehring, 2014). Notably, there are several biases of information processing which have been identified when in states of anxiety (de Jong, 2014), two of which are described below.

One bias attributed to anxiety is the anxiety-linked attentional bias. In principle, this bias should mean that people with high levels of anxiety will be more likely to attend to threatening information in the environment at the expense of less threatening information, maintaining their raised anxiety (Beck et al., 2005). This bias has been observed in numerous studies using different stimuli, such as words, narratives, and images (Bar-Haim et al., 2007). Alongside immediate attention, a similar trend also appears to apply to long-term recall (Herrera et al., 2017), leading anxious people to over-associate fear-relevant stimuli with negative outcomes. The bias has been used as a target of intervention for anxiety and has been met with some success (E. B. Jones & Sharpe, 2017). However, as with other cognitive biases, the attentional bias does not apply at all times or in all contexts, with variation observed across moods, threat intensity, and personal relevancy (MacLeod et al., 2019; Pergamin-Hight et al., 2015). Nevertheless, it is reasonable to assume that people who are more anxious will be more likely to attend to and recall information that is threatening to them, whatever that might be.

The second distortion of cognition applied to anxiety and anxiety disorders is the expectancy bias, which means that anxious people have priors that predict more frequent and more severe threats (Aue & Okon-Singer, 2015). These priors and their effects have been observed both behaviourally and neurologically (de Jong & Daniels, 2020). Initially arising from the learning of associations that may or may not be appropriate (Fernández et al., 2017), these priors are maintained through rumination and the avoidance of situations where prediction errors or further learning could occur (Gazendam & Kindt, 2012; Olatunji et al., 2008). Notably, predictions of negative events have been associated with the dual-processing account of sensory processing[1], leading to subjective impressions of both more and less pain depending on expectations (Elsenbruch et al., 2012; Legrain et al., 2011). Further, these effects and their emotional accompaniments are modulated by the uncertainty and uncontrollability of expected outcomes (Hefner & Curtin, 2012; Sebastiani et al., 2014).

1.4 Autism & Anxiety

Increased anxiety was recognised in the earliest accounts of autism (Frith & Mira, 1992). This continues to be represented by the prevalence of anxiety disorders among autistic people. Estimates exhibit

[1] In this case, the dual-processing model refers to the distinction between bottom-up and top-down perceptual processes.

substantial variation across studies and sample compositions, yet they indicate that the prevalence of anxiety disorder diagnoses among autistic adults range from 27% to 50% at any given time and over the course of the lifetime (Hollocks et al., 2019; Kent & Simonoff, 2017). Similarly, 56% of autistic adolescents have elevated anxiety (Strang et al., 2012). Using a meta-analysis, Hollocks et al. (2019) estimated social anxiety to be the most common disorder (29%), followed by Obsessive Compulsive Disorder (24%), and Generalised Anxiety Disorder (18%). These trends are slightly different than those observed in children and adolescents, where the most common disorder appears to be Specific Phobia (30%; van Steensel et al., 2011). While these figures should be treated with some caution given the similarities between the presenting features of anxiety and autism (Wood & Gadow, 2010), the disruption caused by this raised anxiety is significant, with anxiety consistently being found to be a negative predictor of several aspects of quality of life (Adams et al., 2019; Mason et al., 2018). Anxiety features prominently in qualitative analyses and accounts of lived experience (Milner et al., 2019; Ozsivadjian et al., 2012; A. E. Robertson et al., 2018), with autistic people reporting that their anxiety is one of the most challenging aspects of their experience, raising barriers to their lives and reducing well-being (Trembath et al., 2012).

A complication in the translation of anxiety research conducted in the non-autistic population is that anxiety can be expressed in very different ways in autistic people. As a case in point, autistic people and particularly autistic children have a higher propensity to develop untraditional phobias, such as loud noises, beards, or toilets (Kerns et al., 2014). These phobias likely arise from experiences that would not be perceived negatively by non-autistic people, such as adverse events arising from sensory processing differences, which can make it difficult for non-autistic people to predict or relate to.

Autistic people may also use different techniques to soothe themselves if they find themselves feeling anxious. ‘Repetitive motor behaviours and special interests’ are well documented, being found both in original descriptions of autism and current-day diagnostic materials (Rosen et al., 2021). For example, behaviours that the autistic community term ‘stimming’ involve stimulating the nervous system in a satisfying way, whether through the movement of the body like rocking back and forth, listening to the same musical tracks, or flicking fingers in front of the eyes (W. Dunn, 1999; A. E. Robertson & Simmons, 2015; Rodgers et al., 2012). Special interests are instead very strong interests or passions in subjects which can often be quite specific. Although categorising these interests is complex, it is widely accepted that autistic men typically show an inclination towards mechanical or computational subjects (Nowell et al., 2019), whereas autistic women tend to be drawn to television series and psychology (Grove et al., 2018).

Stimming and special interests are frequently perceived negatively and seen as valid targets for intervention (Patterson et al., 2010). This is because they can be received poorly in social contexts with non-autistic people, being seen as off-putting and disrupting the flow of conversation (Anthony et al., 2013; Collis et al., 2022). They have also been associated with lower psychological well-being (Grove et al., 2018).

Leaving aside issues of cross-neurotype communication (Davis & Crompton, 2021), Grove et al. (2018) note that it is probable that special interests offer positive effects and relief in times of distress, albeit disruptive in some cases. This conclusion is further supported by interviews with autistic adults conducted by Collis et al. (2022) and Kapp et al. (2019), who identified that the suppression of these behaviours only caused further distress.

Another attribute that is thought to be crucial to the autistic experience of anxiety is Intolerance of Uncertainty. Intolerance of Uncertainty is a trait characterised by a strong preference for predictability and difficulty in dealing with unexpected or ambiguous situations (Carleton, 2016). Intolerance of Uncertainty has long been understood as a contributor to anxiety, being included in the diagnoses of generalised anxiety disorder (Carleton et al., 2012) and social anxiety (Boelen & Reijntjes, 2009). While associated with many aspects of anxiety disorders, Intolerance of Uncertainty has been psychometrically demonstrated to be distinct and useful in its own right (Bottesi et al., 2019).

Autistic people will often report that they feel substantial distress at the prospect of uncertainty (Ashburner et al., 2013). Illustrative cases of this can be found in situations where assessment outcomes are uncertain or when there are disturbances to customary daily routines (Bogdashina, 2016). Initial work found that autistic adolescents had higher Intolerance of Uncertainty as measured using a questionnaire than their non-autistic peers (Chamberlain et al., 2013). Follow-up studies then confirmed that the correlation between Intolerance of Uncertainty and anxiety is similar in magnitude to what is found in non-autistic people (Jenkinson et al., 2020). Further, a study of autistic adolescents found that while they had higher anxiety than a non-autistic group, this difference was entirely accounted for by Intolerance of Uncertainty (Boulter et al., 2014). This finding would suggest that the anxiety experienced by autistic people is not inherent to the neurotype and instead follows similar mechanisms to those experienced by non-autistic people.

1.5 Autistic Sensory Reactivity & Anxiety

Sensory reactivity has been strongly associated with anxiety in autistic people across numerous studies (Vasa et al., 2020). This includes studies using correlational analyses (Mazurek et al., 2013), sensory subtypes (Uljarević et al., 2016), adult samples (Hwang et al., 2020), and child samples (Neil et al., 2016). Sensory hyper-reactivity, in particular, has been implicated (Carpenter et al., 2019), rather than hypo-reactivity. Despite variations in effect sizes across different aspects of anxiety (Black et al., 2017), the relationship between sensory reactivity and anxiety shares enough commonality to be considered a legitimate area of study.

Green & Ben-Sasson (2010) described three different theoretical models which could explain the connection between sensory reactivity and anxiety. In the Primary Anxiety model, high levels of anxiety cause higher sensory reactivity. The mechanism underlying this proposed pathway is that heightened anxiety leads to an intensified vigilance towards the sensory environment, which is characterised by attentional and expectancy biases observed in research on neurotypical anxiety (Aue & Okon-Singer, 2015; Bar-Haim et al., 2007; Beck et al., 2005). This model is supported by findings showing a relationship between sensory processing and attention differences in autistic people (Dellapiazza et al., 2018). For example, increased sensory hyper-reactivity and attentional difficulties have been shown to cluster together (Liss et al., 2006). Additionally, it has been observed that autistic children tend to allocate more attention toward sensory stimuli and experience challenges in shifting their focus elsewhere (Sabatos-DeVito et al., 2016). Green & Ben-Sasson (2010) noted in their paper that an issue with this account is that hyperarousal has not been consistently identified using physiological measures with autistic people (Rogers & Ozonoff, 2005).

Green & Ben-Sasson (2010) introduced the Primary Sensory Over Responsivity model as a contrasting viewpoint, which contends that sensory processing differences are the root cause of heightened anxiety experienced by autistic people. In this model, increased hyper-reactivity leads to more stimuli being perceived as extremely unpleasant and, therefore, acts as an unconditioned stimulus in learning models of anxiety and phobias (Boddez et al., 2014). The uncontrollability and uncertainty inherent to sensory stimuli (Reynolds & Lane, 2008) leads to an anxiety response which is more generalised in its activation and behavioural reaction. Since the publication of Green & Ben-Sasson (2010), a considerable body of evidence has emerged supporting the Primary Sensory Over Responsivity model as an explanation for the relationship between sensory reactivity and anxiety. First, longitudinal studies find that sensory reactivity develops first and remains stable in toddlers with anxiety arising later (Green et al., 2012) and experiments have shown a raised autonomic response to sensory stimuli (Jung et al., 2021; S. J. Lane et al., 2012). Finally, autistic people themselves also report that their sensory experiences directly lead to them feeling more anxious when navigating their lives (MacLennan, O'Brien, et al., 2021; A. E. Robertson & Simmons, 2015; Verhulst et al., 2022).

The third and final model posited by Green & Ben-Sasson (2010) is that there is not a direct causal link between anxiety and sensory reactivity. Instead, there may be a common factor through which they are associated. Green & Ben-Sasson (2010) offer differences in the amygdala's function and overlapping diagnostic criteria as plausible explanations that fit this model. The amygdala is central to the emotional response toward sensory stimuli, especially those stimuli related to social cues (Gothard, 2020; Zald, 2003). The amygdala has also been found to have functioning that diverges from population norms in both autistic and anxious people (Linsambarth et al., 2017; S. Wang & Li, 2023), including in response to sensory stimuli (Green et al., 2015). Both autistic sensory reactivity and anxiety could then be explained by an enlarged and overactive amygdala projecting onto cortical areas such as the hippocampus (Green & Ben-Sasson, 2010; Stein et al., 2007), leading to the development of disruptive associations between everyday experiences and a fear response.

One challenge in researching anxiety and sensory reactivity is the shared nature of many of their indicators. This means that a very high proportion of people being assessed for anxiety also score highly on sensory measures (Conelea et al., 2014) and vice versa (McMahon et al., 2019). Ben-Sasson et al. (2007) poignantly demonstrated this by asking occupational therapists and psychologists to distinguish between items from a sensory questionnaire and an anxiety questionnaire, both designed for toddlers. The results revealed that most items were rated as belonging to the wrong questionnaire by at least one professional. Moreover, professionals displayed a preference for assigning items to the condition with which they were most familiar. Recent research has suggested that anxious and autistic people may express different neurological mechanisms in the relationship between anxiety and sensory reactivity (Cummings et al., 2023), but for the moment, the overlap should be kept in mind.

Another challenge arises from the fact that anxiety and sensory reactivity, commonly perceived as unidimensional concepts, manifest in multiple forms. This has led to many attempts to identify the most appropriate theoretical underpinnings for multiple psychometric tools (Ausderau, Sideris, et al., 2014; Knowles & Olatunji, 2020; Takayama et al., 2014). These concerns are relevant because there may be interactions between sub-concepts of both (MacLennan et al., 2020). For example, sensory reactivity is thought to have little impact on the development of social anxiety (Spain et al., 2018) and hyper-reactivity is more associated with anxious behaviours than hypo-reactivity (Carpenter et al., 2019; Pfeiffer et al., 2005). Research attempting to control for levels of autistic traits further complicates this by finding both positive and negative correlations between anxiety and sensory reactivity subscales (MacLennan et al., 2020). A better understanding of the distribution of anxious and sensory reactive traits may help reduce some of the uncertainty around these interactions.

The latest research has combined sensory reactivity, Intolerance of Uncertainty, and anxiety into a single path model (Wigham et al., 2015). Stimming behaviour in autistic people, as described by this model, results from both sensory hypersensitivity and hyposensitivity, prompting the use of motor movements to maintain internal homeostasis. Meanwhile, sensory hypersensitivity is defined as increasing Intolerance of Uncertainty, which increases anxiety, which is finally expressed as behaviours that encourage sameness. This model was initially defined by Wigham et al. (2015) using school-age children and has since been replicated in adults (Hwang et al., 2020) and pre-school children (MacLennan, Rossow, et al., 2021). It has also been shown to better fit psychometric data than other theoretical alternatives (Normansell-Mossa et al., 2021). We can therefore be confident that intolerance of uncertainty has at least some role in the development and maintenance of the relationship between sensory reactivity and anxiety.

An interesting development in this field involves the incorporation of predictive coding models to explain sensory processing within the framework of Intolerance of Uncertainty (Neil et al., 2016; Stark et al., 2021a). As the basis for this model, anxiety arises when predictions are not matched by bodily observations

(Paulus & Stein, 2006). If autistic people are more likely to have a mismatch between priors and observations, as predicted by both predictive coding accounts (Lawson et al., 2014; Pellicano & Burr, 2012; Sinha et al., 2014; van de Cruys et al., 2014), then they would be more likely to experience anxiety. This would be especially notable in situations where uncertainty is present, leading to something similar to Intolerance of Uncertainty. At the current time, this formulation is little tested and there are some complexities to consider (Bervoets et al., 2021; Stark et al., 2021b), but the line of inquiry is promising.

Over time, more factors continue to be added to the model proposed by Wigham et al. (2015). One example of these additions is alexithymia, a multidimensional construct that refers to difficulties in recognizing or articulating one's own emotions, as well as a cognitive bias towards external factors rather than internal states or processes (Preece & Gross, 2023). Not only have increased levels of alexithmia been consistently identified in autistic people, (Kinnaird et al., 2019), but measures of alexithymia have been associated with sensory processing and anxiety both individually (Milosavljevic et al., 2016; B. F. M. Oakley et al., 2022) and within more complex structural models (Riedelbauch et al., 2023). The exact relationship between alexithymia and interoception has been a matter of some debate (Brewer et al., 2016; J. Murphy, Brewer, et al., 2018), with several studies finding that alexithymia better predicts interoceptive difficulties than diagnostic labels like autism (J. Murphy, Catmur, et al., 2018; Shah et al., 2016) and others not replicating those findings (Zamariola et al., 2018).

The broader Wigham model contains potential intricacies that remain unexplored, the first of which is the directionality of the relationships. The Wigham model uses the primary sensory over-responsivity model, where sensory sensitivities lead to anxiety, which is then mediated by intolerance of uncertainty. As previously described, this has a basis in the literature, with longitudinal research finding that sensory sensitivities emerge in caregiver-based reports first and then with anxiety increases later (Green et al., 2012). Similarly, statistical models based on the primary sensory over-responsivity model have been found to be a better fit of cross-sectional data (Amos et al., 2019). Yet, despite the significant body of work supporting the sensory over-responsivity model, there are indications that this evidence base is not be entirely secure. Hwang et al. (2020) noted that reported anxiety peaks during adolescence and both Baribeau et al. (2020) and Hwang et al. (2020) found that repetitive behaviours as scored using the *Autism Diagnostic Interview-Revised* (Lord et al., 1994) in children were highly predictive of future reported anxiety. If higher levels of anxiety lead to children self-soothing through stimming or engaging in special interests, these findings imply the children were already experiencing anxiety that was not entirely captured by the caregiver-report measurements, an issue which has been previously identified (Millington et al., 2021).

It was mentioned by Green et al. (2012) that anxiety and sensory sensitivities could influence each other in either direction. Qualitative evidence from autistic adults suggests that their sensory reactivity can be exacerbated when they feel anxious (MacLennan, O'Brien, et al., 2021; A. E. Robertson & Simmons, 2015) which can be problematic when the anxiety arises from the anticipation of a sensorily adverse experience. Research on the related Sensory Modulation Disorder has also found that traumatic experiences can induce sensory processing difficulties (Yochman & Pat-Horenczyk, 2019).

The second and related issue with our current understanding of the relationships between sensory sensitivities, anxiety, and Intolerance of Uncertainty are often questionnaire-based. As a significant proportion of research regarding autistic people is conducted in children, this can lead to issues regarding the correct perception of their internal states. For example, Keith et al. (2019) found that the self-reported anxiety of adolescents was significantly related to physiological anxiety, while no such relationship was found for the caregiver-report questionnaire. Questionnaire data also captures longer-term trends, asking participants to consider how they typically feel or what they have experienced over the last few weeks. This approach works well when researching the primary sensory over-responsivity model because the effects will be long-lasting. However, the mechanisms of the primary anxiety model described in Green & Ben-Sasson (2010) are micro-phenomena occurring in the short term.

1.6 Aims of This Thesis

The aim of this thesis is to explore the causality of the relationship between anxiety and sensory reactivity in autistic people. Autistic people experience more anxiety and are diagnosed with more anxiety disorders than the general population, which has a direct and negative impact on their quality of life. Differences of sensory processing between autistic and non-autistic people are more complex, with both positive and negative aspects. However, the sensory environment is often outside of an autistic person's control, leading to anxiety and its negative effects on wellbeing. By improving the collective understanding of the links between the two, autistic people may be better able to understand their own experiences and prepare for them. There may also be implications for how society designs and organises shared spaces.

The question of causality between anxiety and sensory reactivity was explored in a couple of different ways, alongside some additional research questions which could affect the relationship. The first study (Chapter 2) was a novel qualitative survey, co-produced with autistic people, examining experiences of sensory overload. Sensory overload has been relatively under-researched, often bundled with other sensory phenomena or investigated in the context of in-patients in hospital wards (Phung et al., 2021; Scheydt et al., 2017). As sensory overload is among the most extreme sensory experiences and features prominently in autistic accounts of sensory processing (MacLennan, O'Brien, et al., 2021; A. E. Robertson & Simmons, 2015; Smith & Sharp, 2013), insights from this study could be invaluable for understanding autistic sensory processing more widely and offering potential frameworks of interest. The study was also an opportunity to observe whether anxiety featured as a contributory factor to the onset of sensory overload without prompting from the researcher.

The second study (Chapter 3) was a methodological chapter, describing the development and validation of a shortened version of the Glasgow Sensory Questionnaire (A. E. Robertson & Simmons, 2013). The Glasgow Sensory Questionnaire has been well-used to measure sensory reactivity associated with autistic people. It has been translated into multiple languages (Sapey-Triomphe et al., 2018; Ward et al., 2021; Zeisel et al., 2023) and has been adapted for both child self-report and caregiver-report (Millington et al., 2021; Smees et al., 2023). The original questionnaire covers seven different modalities and considers both hyper- and hypo-reactivity, in contrast to other questionnaires which typically use different theoretical models or explore fewer modalities. A consequence of this depth is that the Glasgow Sensory Questionnaire is relatively unwieldy. This second study was therefore intended to develop a tool with similar strengths to the long-form Glasgow Sensory Questionnaire but sacrificing some precision for brevity.

The third study included in this thesis (Chapter 4) modelled the cross-sectional relationships between sensory reactivity and traits associated with several neurodivergent conditions – ADHD, autism, and dyslexia. Neurodivergent conditions are often highly heterogenous within a diagnosis while also co-occurring with each other (Masi et al., 2017; Peterson & Pennington, 2015; Rong et al., 2021). Sensory processing differences transcend diagnostic boundaries, as they have been found to be more common in people with ADHD, autism, and dyslexia (Brimo et al., 2021; Panagiotidi et al., 2018; A. E. Robertson & Simmons, 2013). This seems particularly significant in relation to the association between autism and ADHD, as studies have revealed that individuals who have both conditions display the most pronounced differences in sensory reactivity (Dellapiazza et al., 2021). By using a modelling approach, this study aimed to disentangle the different conditions and identify whether sensory reactivity is better identified as an autistic trait or is associated with neurodivergence more widely.

The final study of this thesis (Chapter 5) used a novel Virtual Reality experimental paradigm to test whether manipulations of state anxiety resulted in changes in sensory processing. Based on the findings from Chapter 2, it was believed that perceptual capacities were a potential mechanism for anxiety to influence sensory processing. According to the general load theory, the brain has a limited capacity to process information, which is always fully utilised (Lavie, 2005). In situations with a low demand on this cognitive resource, distracting stimuli are more likely to be processed. Experiments using dual-task paradigms have previously identified autistic people as having an increased perceptual capacity compared to non-autistic people (Remington et al., 2009; Remington & Fairnie, 2017). Effects on perceptual load had also been identified in anxious people, though the direction of action is less consistent (Berggren et al., 2015; Sadeh & Bredemeier, 2011). If state anxiety were found to have an effect on perceptual capacity, a causal link from anxiety to sensory processing associated with autistic people would have been identified.

2. Autistic Accounts of Sensory Overload and Implications for Sensory Reactivity

2.1 Abstract

Autistic people often speak about sensory overload as a highly negative impact on their daily life and wellbeing. Despite this community prominence, relatively little research has explored the concept itself and the research that has been conducted has mostly used clinician reports. This study, co-produced with autistic people, recruited 78 self-identified autistic adults to complete a qualitative survey about their experiences of sensory overload. From the data, two themes about the nature of sensory overload were developed: a functioning perspective and a 'Fight, Flight, Freeze' perspective. Three further themes constructed from the data related to the overload of high-level processing, the overload of low-level processing, and the fatigue associated with sensory overload. These findings have implications for our understanding of the experience of sensory overload and how we envision autistic sensory processing more generally.

2.2 Introduction

Sensory overload is a prominent feature of autistic accounts of sensory processing. In qualitative studies, autistic people discuss how different triggers are unpleasant and also likely to send them into overload (Elwin et al., 2013; R. S. P. Jones et al., 2003; A. E. Robertson & Simmons, 2015; Smith & Sharp, 2013). Implicit in all these accounts is that sensory overload itself is unpleasant and should be avoided beyond the triggers themselves. Without relief or intervention, autistic people report 'shutdowns' and 'meltdowns', experiencing extreme distress and disengaging from the environment (MacLennan, O'Brien, et al., 2021).

While sensory overload is a term that has been well used by both the autistic and research communities, a consensus has not been reached as to precisely what it is. Research into sensory overload has primarily occurred in the psychiatric setting, where patients with ADHD, autism, and schizophrenia can encounter difficulties with the ward environment (Strömberg et al., 2022; Wung et al., 2018). Research into similarities of sensory processing differences across neurodivergences is ongoing, see Chapter 4, but it seems likely that all these groups are experiencing comparable phenomena.

As part of the search for consensus regarding the phenomenology of sensory overload, several definitions and significant features have been proposed (Scheydt et al., 2017). Roy & Andrews (1991) proposed the simple, yet effective 'Increased stimulation to the point of too much to process appropriately'. Goldberger (1982) expanded on this point by including the caveat that the sensory stimulation becomes overloading when it has increased relative to baseline, rather than passing an absolute threshold. An alternative characterisation put forward by Behrens (2003) is that sensory overload arises when a person's coping strategies become insufficient for handling the incoming sensation. The distinction here is that the sensory input does not have to increase. Equally, cognitive strategies to avoid overload may become less effective, for whatever reason that might be. Thus, the experience and onset of sensory overload can be different both between people and across time (Behrens et al., 2012).

In both definitions, the key position is that sensory overload is caused by sensory input which comes to overwhelm the person's sensory capacity. Specifically, this is defined as the sensory input, divorced from any information carried by that sensory input (Lipowski, 1975). Notably, social communication is considered an informational input and would therefore not contribute to sensory overload, according to this dichotomy (Suedfeld, 1985). However, in an account of her lived experience, Williams (1996) emphasised that information overload can lead to sensory overload.

There is also the question of which sensory inputs are relevant. Experts in the Delphi study completed by Scheydt et al. (2016) believed interoceptive sensations and hallucinations could contribute to sensory overload, yet the authors could not identify research findings which supported this belief. There was also a similar belief that sensory stimuli should be subjectively perceived as negative to contribute to sensory overload, in line with stress models (Lazarus & Folkman, 1984) and autistic reports of day-to-day sensory experience (A. E. Robertson & Simmons, 2015). Nonetheless, efforts of definition also differentiate between overload as a result of sensory input and states caused by the reaction to the sensory stimuli (Scheydt et al., 2017), similar to the distinctions made between the levels of analysis articulated by He et al. (2023).

Several reactions to sensory overload have been identified in the literature and expert accounts (Scheydt et al., 2016, 2017). These include physiological stress reactions, such as increased heart rate and blood pressure (Venes, 2017), difficulties in filtering information and higher cognition (Wied & Warmbrunn, 2013), and a detachment from the sensory environment (Lindenmuth et al., 1980). It has also long been observed that people use strategies to escape or reduce their sensory inputs, whether those be physical, cognitive, or some combination of the two (Behrens et al., 2012; Lipowski, 1975). While these reactions were not identified solely in autistic people, they corroborate with accounts of experiences from autistic writers (Grandin, 1996; Willey, 2014; D. Williams, 2015).

At the current time, the research literature contains no accounts from neurodivergent people themselves about their experiences of sensory overload, except for Süllwold & Huber (2013) who spoke to schizophrenia patients and wrote their report in German. We can make some inferences based on the observations of experts (Scheydt et al., 2016), the memoirs of autistic writers (Grandin, 2006; Willey, 2014; D. Williams, 1996), and references made in more general accounts of sensory reactivity (MacLennan, O'Brien, et al., 2021; A. E. Robertson & Simmons, 2015). However, there may remain holes in our understanding resulting from this imprecise method. This study therefore aimed to ask autistic adults directly about their experiences of sensory overload to gauge where knowledge gaps might exist.

2.3 Methods

2.3.1 Participants

The participants in this study were all self-identified autistic people. The decision was made to not require diagnostic validation to mitigate issues of unequal access to diagnostic services (Russell et al., 2022). Participants were recruited through a combination of the University of Glasgow's 'Keeping in Touch' participant database and Neurodiversity Network, and social media posts on *Twitter* and *Facebook.* Participants were then directed toward *Qualtrics* (*Qualtrics*, 2005) to complete the questionnaire. Among the 143 participants who started the questionnaire, 65 individuals chose not to continue with all the questions, signifying their withdrawal of consent and their data were deleted. All participants provided their informed consent prior to beginning the study and ethical approval was given by the University of Glasgow's College of Medical, Veterinary, and Life Sciences ethics committee.

Complete data were collected from 78 autistic adults aged between 19 and 68 (mean = 42.51, SD = 11.42). 2 participants chose to not disclose their age. Gender and educational level characteristics of the sample can be found in Tables 2.1 and 2.2. The collection of ethnicity data was omitted because of concerns about data protection.

Table 2.1

Gender characteristics of participants

Gender	N
Woman	55
Man	10
Non-binary or genderqueer	9
Another gender	2
Woman & non-binary or genderqueer	1
Not disclosed	1

Table 2.2

Highest educational qualification achieved by participants

Education Level	N
GCSE/Standards	2
A-Level/Highers	9
Diploma/Higher Apprenticeship	9
Undergraduate Degree	28
Postgraduate Degree	29
Not disclosed	1

2.3.2 Measures

In the early stages of this project, autistic people from the University of Glasgow's Neurodiversity Network were invited to guide the direction and methods of the project. This led to an online focus group of 5 autistic adults, with Elliot Millington as the moderator. Group members could participate in any way they felt comfortable, such as the optional use of video and voice functions. The discussion was centred around an online text document that was available before and during the focus group. All participants were compensated £15 for approximately 90 minutes of their time.

During the focus group, it was decided that sensory overload would be an appropriate topic of study and that an online survey would be an effective method of studying the area. Eight questions were decided upon and separated into five blocks. The first question explored autistic peoples' different interpretations of what is meant by sensory overload. The second and third questions then asked participants to describe what they experienced during and after sensory overload. These questions aimed to use participant responses to explore the phenomenology of sensory overload and to distinguish it from other sensory experiences. The remaining five questions explored what experiences or active behaviours made sensory overload more or less likely. It was expected that these questions could provide insight into the contributing factors of sensory overload and facilitate the creation of a resource to avoid sensory overload for autistic people. The completed wording of the questions was:

1. What does sensory overload mean to you?

2. When you are in a state of sensory overload, what do you typically experience and feel? For example – what does your body do and what do you think?

3. After an episode of sensory overload, what do you typically experience or feel and for how long?

4. What are common triggers of sensory overload for you?

5. What strategies or coping mechanisms do you use to prevent sensory overload from happening?

6. What strategies do you use when dealing with sensory overload?

7. What have you identified that makes it more likely you will experience sensory overload?

8. What have you identified that makes it less likely you will experience sensory overload?

2.3.3 Analysis

The data were analysed using reflexive thematic analysis as described in Braun & Clarke (2006) and Braun & Clarke (2021). The data were analysed and codified using NVivo 14 (*NVivo*, 2023) by Elliot Millington. Categories and themes were then developed by Elliot Millington and were checked by David Simmons. We used an inductive approach, where our conclusions were driven by the emergent themes from the data.

Member checking of the developed themes was undertaken using a synthesised analysed data method (Birt et al., 2016). The themes were summarised in understandable language alongside supporting quotes, a copy of which can be found in Appendix 8.3. Participants who agreed to be contacted were then asked whether the analysis matched their experience, whether they would want to change anything, and whether they would want to add anything. 49 participants offered their contact details and were contacted for feedback, which was integrated into the themes as part of the iterative process.

2.4 Results

The iterative analytical process led to the development of 5 themes and 11 subthemes relating to sensory overload. These themes included the functional and fight, flight, and freeze response perspectives on the definition of sensory overload, the effects of high sensory load on the lower-level and higher-level sensory processing capacities, and the role of fatigue.

2.4.1 Fight, Flight, Freeze Response Perspective of Sensory Overload

Almost all respondents referred to the acute stress response, also known as the fight, flight, or freeze response, with regard to sensory overload. A few used these terms explicitly in their responses:

“My sympathetic nervous system responds accordingly, resulting in fight/flight/freeze.” IJ

“Panic, fight or flight reaction, want to cry.” LN

Other participants made more implicit reference to the response. For example, many of these were descriptions of physical reactions, such as raised heart rates, quickened breathing, and sweating. Others spoke of the emotional effects, which included irritation, upset, and anger. Escape from the incoming sensations, whatever those might be, was emphasised – voluntarily if caught early, involuntarily if not. Given this understanding of sensory overload, some participants explicitly used physiologically calming techniques to combat the rising tide. Many others used stimming for the same purpose.

Physical Response to Sensory Overload

The initial physical reaction to sensory overload was often tightly related to the acute stress response. This process engages the body to better physically respond to threats, increasing blood flow, sugars, and oxygen, as well as muscle tension (Ulrich-Lai & Herman, 2009).

‘I get hot, sweaty, rapid yet shallow breathing. Heart racing. Shaking. Nothing makes sense.’ WH

‘When it’s multiple sensory inputs then I can feel as though my blood sugars have dipped (they’ve been tested, it’s not that); I get shaky hands and knees, I break out in a sweat.’ PA

Several participants also mentioned negative effects associated with the acute stress response in both the short and medium term (Chu et al., 2023).

‘Sometimes I begin to sweat, or feel faint and fall down, or get stomachache and diarrhoea.’ ES

Emotional Response to Sensory Overload

Unsurprisingly, a negative emotional response during sensory overload was described by nearly every participant. However, the type of response varied between and within people, often dependent on the extent of the overload. Some participants depicted themselves as becoming increasingly upset. Others, in keeping with the acute stress response, explained how they felt panic and anger.

‘Very anxious, sometimes manifests as anger and sometimes makes me want to cry. It can make me feel tense all over. i will actually be thinking, “STOP, STOP, STOP!”’ RA

‘Initially, I feel panic, I often sweat, I wince. I may lose my temper or feel otherwise upset.’ SR

‘Low level overload I get MEAN and ANGRY. Fight/flight reflex is triggered.’ OX

Similarly, anxiety and distress during sensory overload also came through strongly from participant answers as both a defining feature and effect of sensory overload. These feelings could remain for some time after the responsible sensory inputs have subsided.

> ‘When a series of smaller or one larger sensory triggers cause me to be anxious, overwhelmed or unable to cope anymore.’ DG

> ‘It means feeling a very high level of distress due to too much sensory input.’ WB

> ‘I am on edge for awhile afterward, maybe a couple hours, maybe the rest of the day’ ZZ

Behavioural Response to Sensory Overload

Some of the behavioural expressions of sensory overload could be easily mapped to the acute behavioural response. For example, most participants mentioned escaping the responsible environment as their key reaction to sensory overload.

> ‘Escape!!’ WY

> ‘I am scrambling to get away like you might imagine if you put a cockroach into a microwave oven. There is really no thought involved, it is a reaction to a sort of pain that is coming from everywhere.’ ZZ

Even though removal from the source of their sensory discomfort is a clear means of relieving distress, a few participants still found themselves freezing in place:

> ‘I typically freeze, when what I actually need/want to do is escape. I’m not sure there is much of a thought process going on; that is another (internal) stimulus which is also too much.’ MC

Finally, some participants found themselves driven to take more direct action against those who are instinctually believed to be responsible for the sensory distress:

> ‘[…] frustration and anger - caused usually by noise, but directed at whomever I’m talking/working/dealing with.’ CW

Calming Strategies

Several participants indicated they used commonplace calming techniques to reduce their acute stress response to sensory overload. These strategies would be used both in the moment of sensory overload and in the aftermath to decompress.

‘I use breathing techniques to reduce sympathetic nervous system activation.’ IJ

‘Some anxiety strategies like 5 things you can see smell hear etc, throwing ice on pavement for emotional sensory overload. I often want to engage in self-harm but most of the time I can do something else more healthy.’ OX

2.4.2 Functioning Perspective of Sensory Overload

When describing their experiences of sensory overload, several participants explicitly defined it in relation to their ability to continue functioning in a situation. This contrasts with the Fight, Flight, Freeze perspective, where the activation of the sympathetic nervous system was the defining feature. According to this functioning viewpoint, it is the disruption of higher-level cognitive processes which is important. This implies that the occurrence of sensory overload does not depend on a specific threshold being exceeded, but rather on the gradual build-up of pressure in response to situational demands.

‘When sensory input from the environment (external), including auditory, visual, tactile, olfactory, vestibular, kinaesthetic and gustatory factors reaches a threshold where it interferes with cognitive or affective function i.e., losing one’s ability to think clearly, or having an emotional reaction to a sensory stimulus.’ NM

‘It’s like when someone rapidly turns up the volume on TV static and it takes over the functioning capabilities of my brain to where there’s no functioning power left to do what it’s supposed to be doing’ KS

2.4.3 Overload of Lower-Level Sensory Capacity

Considering the sensory nature of sensory overload, it is reasonable to expect that early-stage sensory processing would play a crucial role. Participant answers pointed toward a low-level sensory capacity separate from higher-level attentional processes. An autistic person would, therefore, experience sensory overload when the incoming sensory information is greater than the capacity to process it. The concept is eloquently described in this quote:

‘Sensory overload is the point where I cannot contain any more sensory stimuli. The way I explain it to people is using a cup metaphor: every single person has a “sensory cup”, but they may vary in size and volume. Every sensory experience adds some liquid to the cup, but how much varies from person-to-person. For some people, the sound of a loud bang might lead to a teaspoon of liquid being put in the cup, while for someone else that could equate to a quarter of the cup. Same sound, different sensory reaction. Sensory overload happens when our sensory cup is full (perhaps even overflowing) and we need to do something about it.’ GZ

The types of sensory information being processed and filling up this capacity appear to be broad, including both exteroceptive and interoceptive senses. Approaches to reduce the burden on sensory processing resources include reducing the amount of sensory information entering the system or choosing to neglect certain senses for processing.

Interoceptive and Exteroceptive Sensation

Participants were clear that the holistic sensory experience was important when entering sensory overload. Specifically, alongside well-known exteroceptive triggers such as loud noises or bright lights, participants also emphasised the importance of interoceptive sensations like pain, hunger, or emotional distress.

> 'There is simple overload like competing noises, or complex overload like anxiety, hunger, or upset contributing to the severity of the experience of noise (for instance)' CR

> 'Pain (I have chronic pain so it's always present), sounds (either loud or incessant, and especially if coming from several sources), bright light (e.g. sunlight) for too long, irritating touch (e.g. a tag). And generally things that make me tired make it more likely that I'll have sensory overload' SJ

Sensory Limitation

Strategies for avoiding sensory overload or managing it when it occurred were dominated by different techniques for limiting sensory input. These strategies could be separated into avoidance techniques and active mitigations. Avoidance involved staying away from situations that were known to be aversive or where sensory safety was uncertain.

> 'Avoidance. I try not to put myself into situations where I know there will be way too much input. I stay to the outskirts of gatherings, wear earplugs sometimes, avoid some environments altogether, etc.' CB

> 'I try to not go to new, crowded or noisy places' TP

In contrast, active mitigation strategies were used when those situations could not be avoided, such as when shopping or travelling. They were mostly based on minimising sensory input into the passive senses, though emotionally soothing tools or stims were also present. Noise-cancelling headphones with volume-controlled music were popular with many participants.

> 'Listening to music when on the street/bus/busy places to block out all the different sources of noise, cutting out tags and wearing loose clothing, avoiding touching/wearing plastic as much as I

> can, trying to manage my pain, staying inside/pulling the curtains on bright days when I'm already at risk of sensory overload' SJ

> 'I have a "sensory survival kit". I take my phone with earphones everywhere, gum to help regulate, Loops, hand sanitiser, a body spray I like the smell of, sunglasses, a snack. All things that can help me to regulate before it happens.' GZ

Shutdown

High-end levels of sensory overload were described as leading toward two differing outcomes: shutdowns or meltdowns. Shutdowns were described as though the brain was refusing to process any more low-level sensory information, losing conscious awareness of those sensations. This led participants to feel disembodied or living entirely within their heads, unable to remove themselves from the external sensory environment. According to participant explanations, shutdowns are an internalised means of regulating sensory processing demands by excluding specific senses, thereby bringing them within an individual's sensory capacity.

> 'High-level overload (extreme situations, or if I'm unable to remove myself from the mid-level situation), can lead to a complete shutdown. This usually consists of near or complete catatonia, loss of non-speaking communication along with verbal speaking, inability to move or do anything to reduce the sensory input that caused the overload.' OX

> 'I feel sort of invisible and isolated, but in a good way. I'm very in the moment and in my own head.' VW

2.4.4 Overload of Higher-Level Attentive Capacity

While the importance of lower-level sensory processing in sensory overload is self-evident, the role of higher-level processing and/or attention is less obvious. However, many participants were clear that demands on executive function or non-sensory information could contribute to the experience of sensory overload.

> 'I very much identify with the intense world theory of autism and am often overwhelmed with outside information in particular from others. On top of that, too much noise, movement, visual stimulation at once and for too long. Being asked to do too many things at once or being given too much information at once.' BP

> 'Having to make decisions (even small ones, like what kind of cheese to buy) in settings that are sensory stressful or having to participate in social interactions or conversations.' XL

Similarly, various participants reported how they experienced a disruption to their cognition during and around sensory overload, particularly when leading to a meltdown. This suggests that higher-level processing capacities can also be overburdened by large amounts of sensory information, diverting attention from a plethora of other tasks.

> ‘My train of thought becomes foggy and I feel an uncontrollable need to talk. I talk very fast, sometimes I don’t even know what to say but I want to talk so I’ll start a sentence without knowing what I’m going to say.’ AB

> ‘[…] not thinking clearly, not able to make simple decisions (e.g. order dinner, answer questions), decreased balance and co-ordination, increased clumsiness […]’ ON

Alongside more general executive function demands, both anxiety and uncertainty were especially prominent among participant responses as additional demands that could lead to sensory overload.

Role of Emotional Arousal

Most participants said that high levels of arousal - whether that be negative in the form of anxiety, or positive in the form of excitement - made it more likely for them to experience sensory overload. This seemed to result from two different processes. The first was as a contributory sensory input from the interoceptive senses during high arousal or handling anxious thoughts. Second, when anxious, participants reported exerting more effort to process the surrounding environment, leading to more information to be attended to.

> ‘[…] high anxiety, stressful situations where I need to concentrate, talking to someone who may be evaluating me.’ OK

> ‘If i am feeling stressed or thinking about something i need to do or vulnerable or frustrated etc.’ LD

> ‘[…] emotions- too many strong emotions at one time’ OX

Uncertainty

Many respondents mentioned the uncertainty, or conversely predictability, of their sensory environments as a key factor affecting whether they experienced sensory overload. Uncertainty seemed to affect both the magnitude of sensory stimuli and levels of anxiety related to those same stimuli.

> ‘If my very predictable schedule is altered 2 or more days in a row, is a sure bet I will experience sensory overload even without too many/big sensory triggers.’ AB

> ‘Controlled and known environments are good. Planning and knowledge of what to expect in an environment helps remove the element of surprise that often feeds anxiety and sensory overload.’ GZ

2.4.5 Depletion of Energy

It was universal among the participants to feel fatigued by sensory overload, moderated by its severity. Several participants associated this tiredness with other intense experiences, like migraines, suggesting similar mechanisms. The extent of this fatigue directly affected what participants felt they could do in the aftermath, with many saying they would need to sensorily isolate before doing anything else.

> ‘It feels a little like recovering from a migraine episode, a really bad hangover or when psychiatric drugs have been adjusted and your still a little “off” and not quite yourself again yet. How long I feel like it will depend on the severity of the overload. I might be out for a couple of hours, the rest of the day or several days even.’ XL

> ‘Can’t do anything else for the rest of the day. Can’t interact with people any more that day - have to be on my own and quiet - no more input’ AB

Regeneration over Time

Akin to other forms of fatigue, participants clarified that rest was the key to recovering from sensory overload. However, sensory input limitation was essential for this rest to be effective. Many respondents reported retreating to safe, dark, and quiet spaces to recuperate for however long they needed. Unsurprisingly, sleep was a common implementation of this.

> ‘I will feel tired and lacking energy, needing to to things at a very slow pace or just rest. If I have a good night’s sleep after that, I will usually feel ok in the morning. (I tend to have a very light sleep though, so there’s no guarantee of a good night’s sleep.)’ CS

> ‘It is distressing and I will want to go somewhere quiet - in terms of auditory and visual information. I put my head down to reduce what I am seeing, and may block my ears with my fingers or put headphones on.’ BS

Wellness as Resilience

Participants’ general wellness seemed to affect whether they were likely to experience sensory overload. When participants were feeling physically and mentally well, including engaging in good health behaviours, they could cope with more averse sensory stimulation without entering sensory overload.

Conversely, if they were feeling unwell from factors such as recent sensory overload, illness, or their menstrual cycle, they would not respond as well to sensorily unsafe environments.

> ‘Being tired and near a burnout state, needing to mask excessively for long periods of time and in an environment that has bright lights and crowds/lots of conflicting noises mean I am always in a state of being overwhelmed’ GZ

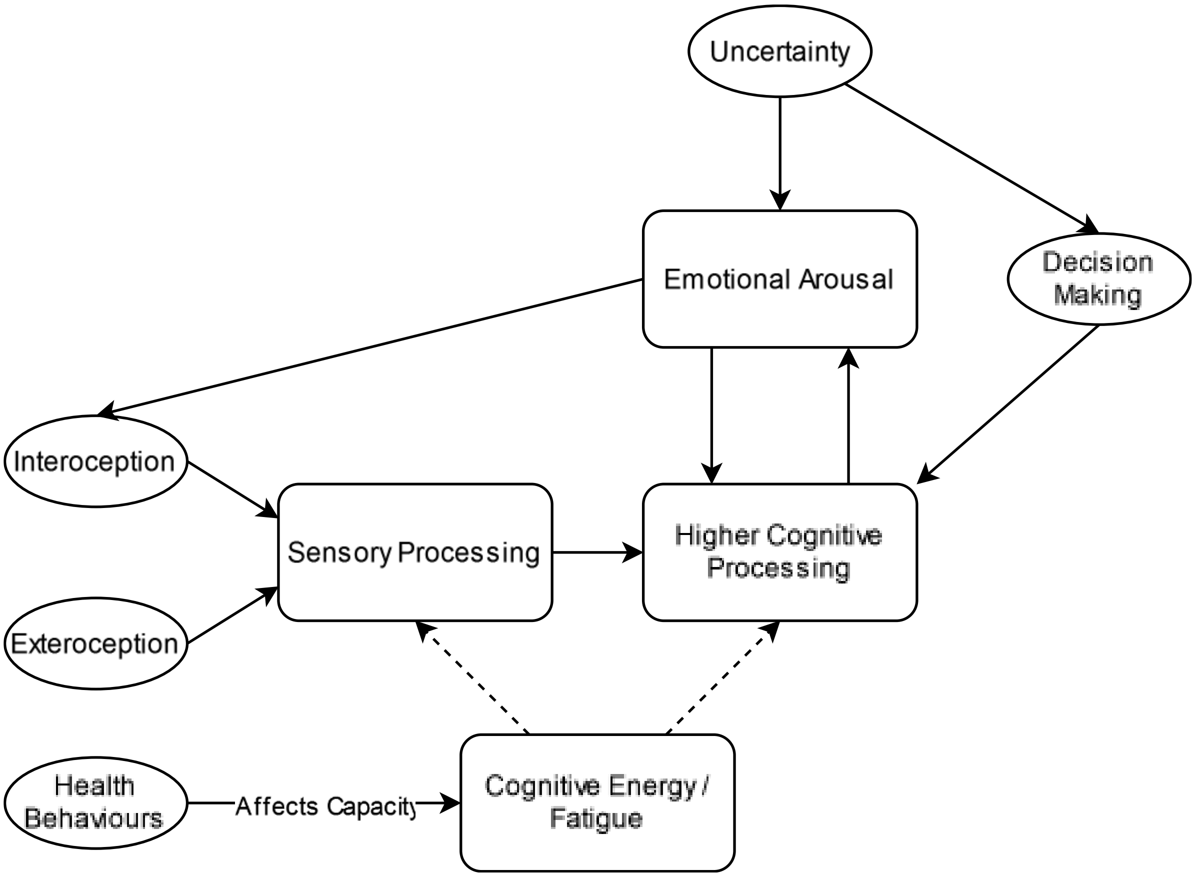
> ‘bad sleep, irritability due to other factors, poor mental or physical health, illness, menstruation, […]’ WA

2.5 Discussion

This qualitative study is one of the first to explore sensory overload from the perspective of autistic individuals. This analysis, which was co-produced with autistic people, utilised thematic analysis to develop five broad themes iteratively. These themes encompass sensory overload as a fight, flight, or freeze response, a functioning perspective of sensory overload, the overload of lower-level processing capacity, the overload of higher-level processing capacity, and the impact of sensory overload on energy levels. In continuation of tradition in qualitative work in this area (MacLennan, O’Brien, et al., 2021; A. E. Robertson & Simmons, 2015; Smith & Sharp, 2013), Figure 2.1 summarises the proposed links between the different themes. This model is not intended to replace previous efforts, but to complement them by considering only what is occurring during sensory overload, which exists at the most extreme end of sensory experience.

Figure 2.1

Proposed model to aid understanding of themes and findings from the thematic analysis of autistic reports of sensory overload.



The first couple of themes in the analysis considered what autistic people understand to be 'sensory overload'. This question was notable considering the moderate disagreement between different scholars (Scheydt et al., 2017). Some participants defined sensory overload in reference to how their sensory processing affected their functioning in the moment, quotes for which can be found in section 2.4.2. This interpretation is more similar to most of the pre-existing definitions in the literature, which focus on the brain's capacity to process incoming sensory information (Goldberger, 1982; Roy & Andrews, 1991). However, the perspective of the participants captured in the 'Functioning Perspective of Sensory Overload' theme is slightly broader. Rather than sensory overload beginning when the perceptual capacity is no longer sufficient to capture all incoming information, sensory overload would instead begin when that under-capacity disrupted the person's ability to continue toward their goals. Some of this difference may have arisen from the differing contexts between participant groups. Most of the work exploring sensory overload at this point has come from institutional care (Scheydt et al., 2017), where the cognitive demands on patients are low and their health needs are high. The participants in this study were reflecting on their lived experience, where the cognitive demands are much higher and they are likely to experience a wider variety of sensory environments.

While some participants took the functioning perspective to define their sensory overload, most participants instead used their physical reaction as the key benchmark which was used to form the ‘Fight, Flight, Freeze Response Perspective of Sensory Overload’ theme. The sub-themes of this theme capture all the consequences that would be expected by an acute stress response, including increases in heart rate, sweating, strong emotions, and a desire to flee from the trigger (Benarroch, 2014). These reactions, when in a state of sensory overload, had been well documented by previous academic descriptions (Scheydt et al., 2016; Venes, 2017) and were consistent between participants. The implication from these participant responses is that they considered overload to be occurring when the acute stress response began.

In both themes exploring what it means to enter sensory overload, the underlying mechanism was still bound to the ability to process sensory information. Rather than a rigid threshold with distinct markers, participants reported that the experience of sensory overload ebbed and flowed depending on the extent to which their processing capacity was being overwhelmed. The difference between the two perspectives is therefore the metric used to judge when adverse sensory inputs have reached a sufficient point to be considered overload. The distinction may also not be particularly useful, as reduced executive function and reasoning abilities are well associated with acute stress (Sandi, 2013). Instead, given the variation in interoception and meta-cognition within both the autistic and non-autistic populations (J. Murphy et al., 2019; Rouault et al., 2018), the distinction between the functioning and stress response perspectives may just be a product of what an individual recognises first.

The key implication from the ‘Interoceptive and Exteroceptive’ sub-theme was that autistic people felt that all incoming sensory information affected whether they entered sensory overload. This included the senses oriented toward the outside world and the internal senses, such as hunger or pain. Notably, the physical and psychological effects of emotional states were also seen as contributory, as seen in the ‘Role of Anxiety’ sub-theme. This finding corroborates the intuitions of experts in Scheydt et al. (2016), who believed that interoceptive sensations contributed to sensory overload, but the authors could not identify supporting evidence for the claim. If interoception has a similar role to exteroception during sensory overload, then it may also have a similar role in autistic sensory processing more generally. For example, the emotional inferential difficulties associated with alexithymia may result from hypo-reactivity in interoceptive systems. This could then also situate the difficulty in finding a consistent relationship between interoception and alexithymia (J. Murphy, Brewer, et al., 2018; Zamariola et al., 2018) within the wider context of inconsistent psychophysical findings in autistic research (Simmons et al., 2009).

During theme development, the processing capacities were separated into lower and higher levels to capture the distinction made by participants between overloads caused solely by incoming sensory information and overloads where more complex cognition was a contributory factor. Given that processing capacities are an abstraction to capture a multitude of neurological bottlenecks (Wenger & Townsend, 2000), this distinction was not felt to be over-presumptuous. In line with autobiographical accounts (D. Williams, 1996), participants were clear that cognitive demands contributed to their feelings of sensory overload, as seen in the quotes in section 2.4.4. This was despite the explicit differentiation between sensory and information overload in the academic literature (Lipowski, 1975; Suedfeld, 1985). The discordance between lived experience and academic understanding could be explained using the split capacity model. While sensory inputs and sensory inputs alone fill the lower-level capacity, increased cognitive demands increase the likelihood that higher-level processing will be overwhelmed and/or for cognition necessary to continue functioning to be displaced in favour of sensory information. As an increase in sensory demands is the proximate cause for the overload, it would be experienced as a primarily sensory experience.

Another phenomenon where this model may be useful is the relationship between meltdowns and shutdowns. The experiences described in this study are like those expressed by autistic people summarised by Belek (2019) and Welch et al. (2021). Meltdowns are described as a feeling of overwhelm that is accompanied by a lack of control, leading to emotional outbursts and instinctual behaviour. Meanwhile, shutdowns are experienced as the cutting off of different systems from cognitive control for the purposes of self-preservation, such as individual senses or the ability to move. Meltdowns have been described as the externalised expression of severe stress, compared to shutdowns which are internalised (F. Murray, 2023). Both are closely related to each other and autistic burnout (Phung et al., 2021). Based on the experiences reported by participants in this study in the 'Shutdown' subtheme, shutdowns appear to be the experience associated with an overload of low-level processing capacity, leading to the percepts of entire senses being neglected. Conversely, meltdowns are more associated with the overwhelm of high-level processing capacities, leading to a loss of emotional regulation. Without research directly addressing these concepts, the usefulness of this perspective remains to be seen.

This dual-level understanding of sensory processing aligns with the attentional theories of sensory processing capacity (Remington et al., 2009) and monotropism (D. Murray et al., 2005). Rather than just having a larger sensory capacity at baseline, higher levels of anxiety may lead autistic people to expend greater effort to expand their sensory capacity. As well as leading to more sensory information being processed at higher levels of cognition, anxiety may then lead to that sensory information being attended to at the expense of other processes, leading to the results observed in dual-task paradigms and reports from lived experience (Remington et al., 2012; Remington & Fairnie, 2017).

The insights from the 'Depletion of Energy' theme have several implications for how we might think about sensory capacities. In the 'Wellness as Resilience' sub-theme, participants reported that their general sense of well-being influenced the likelihood of experiencing sensory overload. Similarly, participants reported that intense sensory experiences were exhausting, requiring them to rest before they could continue with their lives. Otherwise, they would likely be overloaded again. Together, these imply that capacities for processing sensory information are not static but can instead expand or contract depending on the exertion of mental effort. This qualitative finding seems to support experimental work using perceptual load, which has identified fatigue effects on participant performance and therefore perceptual capacity (Csathó et al., 2012). There is also an interesting point of comparison with migraines, which are associated with sensory sensitivity and fatigue (Goadsby et al., 2017; Seo & Park, 2018), and a cycle of neurological over-activity and under-activity (Schwedt et al., 2015). However, while fatigue effects have been observed across many psychological tasks (Aaronson et al., 1999), the precise cognitive and neurological mechanisms underpinning it are unclear (Hockey, 2011; C. Wang et al., 2016).

Anxiety has been one of the longest-running research threads in the context of cognitive performance. Eysenck & Calvo (1992) proposed the processing efficiency theory, which states that anxiety depletes cognitive resources, but anxious people then exert more effort to increase their processing capacity. This would mean they could maintain an equivalent task effectiveness but with reduced resource efficiency. This story would align with the reports from the participants in this study described in the 'Role of Anxiety' sub-theme who wrote about more effortfully directing their attention, as well as using their capacity to process their emotions. However, it is notable that similar experiences were also attributed to arousal of any kind, both positive and negative, in contrast to stress models of sensory overload and previous qualitative work (Lazarus & Folkman, 1984; A. E. Robertson & Simmons, 2015). The processing efficiency theory was then developed by Eysenck et al. (2007) into the attentional control theory, which suggests that anxiety instead primarily affects the distribution of resources towards stimulus-driven attention. This reduces the role of anxiety as a demand on cognitive processing, though compensatory strategies remain (Eysenck et al., 2007; Shi et al., 2019). The attentional control theory is also closer to the mechanisms of the primary anxiety explanation of the relationship between anxiety and sensory processing proposed by Green & Ben-Sasson (2010). There is experimental evidence that raised anxiety leads to effects predicted by a higher perceptual capacity (Berggren et al., 2015), though contradictory results have also been found (Sadeh & Bredemeier, 2011).

A further consideration prompted by the 'Wellness as Resilience' sub-theme is the relationship between sensory overload and autistic burnout. Burnout is again relatively unexplored but is associated with exhaustion, withdrawal, intensified autistic traits, and reduced functioning (Arnold et al., 2023). In this study, several participants in this study explicitly reflected that they were more likely to experience overload when burned out. Previous research has also identified negative sensory experiences as a cause of burnout (MacLennan, O'Brien, et al., 2021). In a conceptual model of burnout constructed by Mantzalas et al. (2022), personal demands including sensory needs directly affect the likelihood of autistic burnout, as well as indirectly impact mental strain (depression, anxiety, and stress) and wellbeing, which themselves indirectly affect burnout. Further, many of the health behaviours described by participants have been shown to impact occupational burnout in non-autistic people (Springer et al., 2023), though it should be noted that autistic and occupational burnout appear to be distinct (Mantzalas, Richdale, Adikari, et al., 2022). The web of connections between these different concepts indicates a vicious/virtuous cycle, whereby improvements or declines in a single factor can have wide-ranging and exponential effects.

Uncertainty has a prominent position in research on autistic peoples' anxiety, with the consensus that autistic people have a higher Intolerance of Uncertainty than non-autistic people and therefore have a stronger anxiety response to uncertainty of any kind (Wigham et al., 2015). Participant narratives included in the 'Uncertainty' subtheme support this account, with some participants reporting how they would be more likely to experience sensory overload following disruptions to their schedule, presumably because of their increased anxiety. Yet, some participants also reported that uncertainty increased the potency of the sensory stimuli as a trigger for sensory overload, especially if the uncertainty was a component of the stimulus itself. This experience could be accounted for by combining the Bayesian and perceptual capacity accounts of autistic sensory processing. In this explanation, increased uncertainty in the sensory input would lead to more processing of that input because of the increased mismatch between the prior and the signal (S. Hu et al., 2015).

The methods by which people handled their sensory overload were the same as autistic people have described handling their sensory needs in their lives more generally. This included the active mitigation and avoidance strategies in the 'Sensory Limitation' sub-theme, as well as moving away from trigger stimuli (MacLennan, O'Brien, et al., 2021; A. E. Robertson & Simmons, 2015; Smith & Sharp, 2013). This similarity reflected the direct connection between adverse sensory events and sensory overload, and was expected. Participants also explained how they used soothing sensory stimuli or stimmed to counteract their sensory triggers, as has been previously documented (A. E. Robertson & Simmons, 2018). However, the techniques described in the 'Calming Strategies' sub-theme have not been placed in a sensory context previously.

2.5.1 Limitations

This study was designed with input from autistic people to be accessible online, removing geographical and time constraints, and avoiding the need to interact with unfamiliar researchers. Unfortunately, this flexibility was at the cost of the researcher being unable to assist participants if they did not fully understand the question or ask them to provide more detail and context in their responses. Similarly, it was necessary for participants in this study to have a strong command of language, excluding individuals with an intellectual disability who remain underserved by research (Russell et al., 2019).

2.5.2 Conclusion

This study offers an initial exploration of sensory overload from the perspective of autistic adults. Based on participant responses, it is reasonable to assume that sensory overload expresses standard autistic sensory processes when limits on processing capacity at low and/or high levels have been reached. The expression of sensory overload then varies between people and depends on the extent and context of the overload. Anxiety also appears to have a unique position as both a consequence and contributor to sensory overload. Future work should explore the concepts described in this study in more depth, especially distinguishing between sensory shutdowns and meltdowns.

3. Development and Validation of the Glasgow Sensory Questionnaire Short

3.1 Abstract

Many autistic people find that differences in their sensory processing present challenges when interacting with the world, especially when not supported. The Glasgow Sensory Questionnaire (GSQ) is a questionnaire that asks questions about the hyper- and hypo-reactivity of the five main senses, as well as proprioception and the vestibular sense. The standard questionnaire contains 42 questions, which can be burdensome for those completing it. This study constructed the Glasgow Sensory Questionnaire Short (GSQ-14) using secondary data from 787 participants and several Confirmatory Factor Analyses. Validation data were separately and specially collected using an online sample of 75 participants who completed the GSQ-14 and Autism Spectrum Quotient (AQ) Short. In the construction sample, the new GSQ-14 was found to have good internal reliability and a significant correlation with the AQ. These results were then replicated in the validation sample. This study has successfully constructed and validated a short version of the GSQ, demonstrating that it is appropriate for wider use. The factor analyses used during the construction also point towards the importance of considering both the hyper- and hypo-reactivity of each sense when researching the sensory processing of autistic people.

3.2 Introduction

Many autistic people find that their sensory experiences differ from those of non-autistic people. Now recognised in the diagnosis of Autism Spectrum Disorder in the DSM-5 (APA, 2022) and ICD-11 (World Health Organization, 2019), approximately 90% of autistic people have differing sensory experiences (Leekam et al., 2007). These differences can be found in both the interoceptive and exteroceptive senses, with any sense potentially being hyper- and hypo-reactive at the same time (Elwin et al., 2013). These reactivities can be expressed behaviourally, with hyper-reactivities believed to lead to avoidance behaviours and hypo-reactivities leading to sensory-seeking behaviour (W. Dunn, 1999).

Sensory processing differences can be further separated into sensitivity, reactivity, and responsivity (He et al., 2023). While these terms have been used interchangeably, sensitivity refers to early processing in the sensory cortices, while reactivity and responsivity refer to the emotional and behavioural response to a stimulus (Schulz & Stevenson, 2019). This distinction means that there can be a disconnect between stimulus and response. For example, an adverse sound may not lead to a reaction due to camouflaging (Cook et al., 2021) or someone may become distressed in anticipation of a sound that has not yet presented itself.

Sensory processing differences can make life difficult for autistic people when not properly supported. In settings such as schools or the workplace where there is little control over the sensory environment, autistic people can be distracted, debilitated, and distressed (E. K. Jones et al., 2020; A. E. Robertson & Simmons, 2015; Smith & Sharp, 2013). Research suggests that repeated negative sensory experiences lead to increased state anxiety, starting in childhood and maintained throughout adulthood (Green & Ben-Sasson, 2010; MacLennan, Rossow, et al., 2021; South & Rodgers, 2017). Given the strong relationships between sensory processing, anxiety, and quality of life (Lin & Huang, 2019), a better understanding and identification of sensory needs will help autistic people lead fulfilling lives.

The most common method of researching sensory processing difficulties associated with autistic people is using questionnaires. For adults able to self-report, these are questionnaires such as the Glasgow Sensory Questionnaire (A. E. Robertson & Simmons, 2013), Sensory Perception Quotient (Tavassoli et al., 2014), or Adult & Adolescent Sensory Profile (Brown & Dunn, 2002). Each of these questionnaires uses slightly different models of autistic sensory processing and combines their items in slightly different ways. For example, the Adult & Adolescent Sensory Profile separates items into four quadrants, defined by whether the neurological threshold associated with the sense is higher or lower than general population norms and whether behavioural responses are passive or active. Alternatively, the Sensory Perception Quotient measures whether a person is more hyper-sensitive or hypo-sensitive across the five classic senses, though an updated scoring system separated them into hyper-sensitive and hypo-sensitive scores (E. Taylor et al., 2020). However, all these questionnaires ask about the frequency of sensory experiences and behaviours commonly linked to autism. It is therefore unsurprising that they all significantly correlate with measures of autistic traits (Horder et al., 2014).

The Glasgow Sensory Questionnaire (Robertson & Simmons, 2013; GSQ) is distinct from the other sensory questionnaires because its items explicitly capture sensory reactivity by asking about sensory processing behaviours. The questionnaire also explores more senses by asking about proprioception and the vestibular sense, alongside sight, smell, hearing, touch, and taste. Multiple translations have been made and validated across the globe, including Chinese (Ward et al., 2021), Japanese (Takayama et al., 2014), French (Sapey-Triomphe et al., 2018), and Dutch (Kuiper et al., 2019). While the original questionnaire was designed to be completed by adults, further versions have been created for caregivers and children (Millington et al., 2021; Smees et al., 2023). In the process of developing the Glasgow Sensory Questionnaire and its extensions, the underlying structure of the questionnaire has been assessed and consistently found to form a single factor representing sensory reactivity. This is despite including subscales representing each sense, as well as both hyper- and hypo-reactivity. The consistency also contrasts with more general attempts to assess the latent structure of sensory reactivity, which have identified a variety of different potential factor or cluster-based solutions (Ausderau, Furlong, et al., 2014; Ausderau, Sideris, et al., 2014; A. E. Lane et al., 2014).

This report will describe the process of selecting a subset of items from the Glasgow Sensory Questionnaire to create a short version. This questionnaire aims to be easier to apply than the long-form version for both researchers and practitioners while still capturing a holistic picture of the participant's everyday sensory experience. The selected items will then have their internal reliability checked and correlated with a measure of autistic traits to assess whether they remain effective.

3.3 Methods

3.3.1 Measures

Glasgow Sensory Questionnaire

The Glasgow Sensory Questionnaire (GSQ), developed by Robertson & Simmons (2013), is a questionnaire-based measure of sensory processing phenomena associated with autism. There are 42 items which are separated into seven modalities: vision, audition, olfaction, gustation, tactile, proprioception and the vestibular sense. Each of the items is further categorised by whether they address sensory hyper- or hypo-reactivity. There are 14 subscales, each containing three items. The items are scored using a five-point Likert scale ranging between 0 (Never) and 4 (Always). Participants can therefore score between 0 and 168 on the questionnaire.

Autism Spectrum Quotient

The Autism Spectrum Quotient (AQ; Baron-Cohen et al., 2001) assesses the level of autistic traits exhibited by an individual. The questionnaire uses 50 items which are divided into 5 subscales: social skills, attention switching, attention to detail, communication, and imagination. Participants respond to each item using a four-point Likert scale ranging from *Definitely Disagree* to *Definitely Agree*. As recommended in Auyeung et al. (2008), rather than using the binary scoring system in the original Baron-Cohen et al. (2001) paper, this study scored responses between 0 and 3, meaning that scores range between 0 and 150. If a participant scores above 76, they are likely to be autistic.

For the validation sample, the short form of the AQ was used (AQ-10), as developed by Allison et al. (2012). To create the AQ-10, two items were selected from each of the five subscales of the long-form AQ based on their discrimination index. For this study, the AQ-10 was completed and scored in the same fashion as described above for the AQ. This means that scores on the AQ-10 can vary between 0 and 30.

3.3.2 Participants

Calibration Sample

The analyses constructing the GSQ-14 were conducted on data collected by Horder et al. (2014). These data were chosen as they were made available for secondary analysis, the participants' first language was English, and the data were stored at the item level for both the Glasgow Sensory Questionnaire and Autism Spectrum Quotient.

The sample comprised 787 participants, all living in the United Kingdom. Of these participants, 566 were female and 221 were male. The mean age of the participants was 25.94 years with a standard deviation of 8.22. 23 of the participants had a confirmed diagnosis of autism spectrum disorder or equivalent, though there may be autistic people in the group without a confirmed diagnosis, and not all participants were asked to disclose. Ethnicity, socioeconomic status, and education levels were not available in these data sets.

Validation Sample

The validation data set was collected purposefully for this study. A bootstrap power analysis using the calibration sample was conducted using the correlation between the AQ-10 and GSQ-14 as the test of interest. This analysis concluded that 71 participants would be appropriate to achieve a power of .95 using an alpha of .05. The recruitment target for participants was therefore set to 75, to allow for some error. Ethical approval for this recruitment was granted by the University of Glasgow's College of Medical, Veterinary, and Life Sciences ethics board.

75 participants were recruited through the *Prolific* platform and completed both the AQ-10 and the GSQ-14 using *Qualtrics* (*Qualtrics*, 2005). Inclusion criteria were that the participants be aged 18 or over, living in the UK, and fluent in English. Responses were screened to ensure that they were authentic, however, no participants were excluded. The sample contained 13 men and 62 women. The mean age of the participants was 40.62 years (SD = 15.13). Tables 3.1 and 3.2 contain further information on ethnicity and education level.

Table 3.1

Ethnicities of the Validation Sample

Ethnicity	N
Arab	1
Asian - Bangladeshi	2
Asian - Pakistani	1
Asian - Other	1
Black - African	1
Black - Caribbean	2
Black - Mixed	1
White - British	57
White - Irish	1
White - Other	3
Other	5

Table 3.2

Highest Levels of Education Achieved in the Validation Sample

Education Level	N
None	1
GCSE/Standards	9
A-Level/Highers	24
Diploma/Higher Apprenticeship	2
Undergraduate Degree	21
Postgraduate Degree	18

3.4 Data Analysis

3.4.1 Theoretical Underlying Structure

Multiple studies have found that the measurement of autistic traits in the neurotypical population forms a normal distribution with minimal to low skew (Baron-Cohen et al., 2001; Ruzich, Allison, Smith, et al., 2015). There is a discussion about whether autistic people represent one tail of this distribution or a separate distribution of their own, though conclusions differ depending on whether samples are enriched with a greater proportion of autistic people than found in the general population (Abu-Akel et al., 2019).

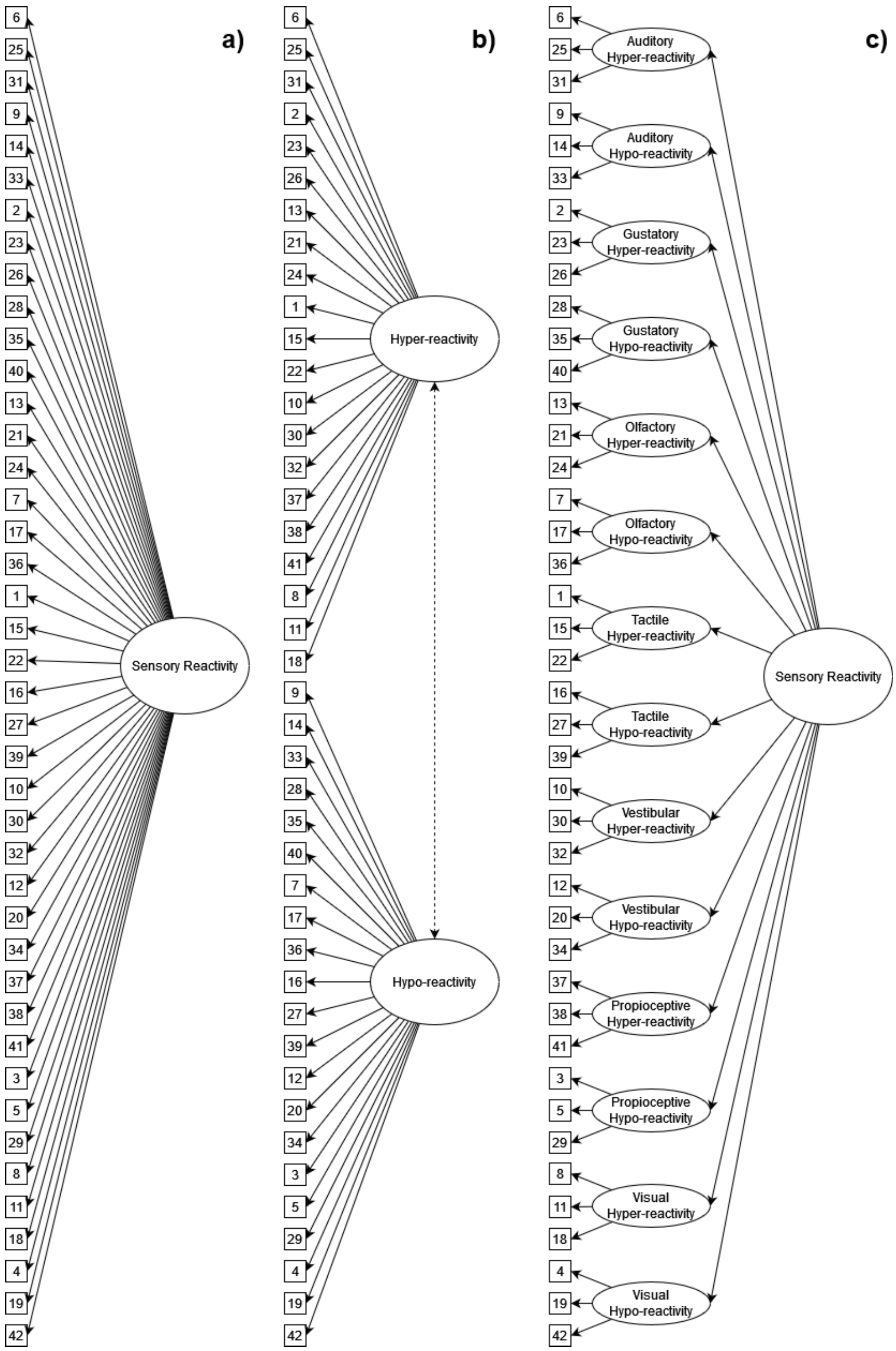
During the development of the GSQ, Robertson & Simmons (2013) suggested that sensory processing follows a similar pattern to autistic traits, supported by a principal components analysis which identified a single notable component. This would imply that there is a single latent variable onto which all items are loaded. However, the inclusion of subscales hints toward some form of hierarchical structure, with each subscale being a latent variable that either covaries or combines to create a general latent variable. Because of these different theoretical structures, several models were tested for this analysis.

3.4.2 Model Specification

Nine confirmatory factor analysis models were initially tested, each of which represented a feasible solution for categorising the items of the GSQ. However, only three solutions could be fully identified. The first of these models loaded all the items onto a single latent variable. In the second model, all items capturing hyper-reactivity loaded onto one factor and items capturing hypo-reactivity loaded onto another. For the final model, the items loaded onto their original subscales. Those subscales then loaded onto a single factor representing general sensory reactivity. These three models are visualised in Figure 3.1.

Figure 3.1

Different potential latent structures of the Glasgow Sensory Questionnaire. Squares represent questionnaire items and circles represent latent factors. Solid arrows indicate a factor loading and dashed arrows indicate covariance. a) A single underlying factor loading onto all items. b) A two factor solution where items are separated by hyper- and hypo-reactivity. c) A second-order factor solution where each combination of modality and reactivity direction forms a factor which each load onto a single 'sensory reactivity factor'.



3.4.3 Analytical Decisions

All the models were estimated using version 0.6-11 of the *lavaan* package in R (Rosseel, 2012). These models used covariance matrices and diagonally weighted least squares as the estimation method. The rationale behind choosing this method was that, even though the overall scores formed an approximate interval scale with a normal distribution, each item response was ordinal. As the items were treated as ordinal variables, the data were not transformed before the analysis. Any participants with missing data were excluded from the analysis.

3.5 Results

3.5.1 GSQ-14 Calibration

Confirmatory Factor Analyses Fits

The global fit indices of the models are listed below in Table 3.3. The model chi-square was significant for all tested models. While chi-square can be overly sensitive in models with larger sample sizes (Kline, 2015), as reported here, these results suggest potential issues with local fit. Inspection of the model revealed all models had items with residuals that correlated with each other. However, no theoretically consistent explanation for these correlations could be identified. It was therefore felt that the current models were good enough for this analysis, if not a perfect reflection of reality.

Table 3.3

A Comparison of Model Fit Statistics for Competing Confirmatory Factor Models of the Glasgow Sensory Questionnaire

	Chi-square	Degrees of Freedom	P-value	CFI	RMSEA	SRMR
Subscales	2501	805	<.001	.967	.052	.066
Hypo/Hyper Reactivity	2806	818	<.001	.961	.056	.067
Single Factor	2941	819	<.001	.959	.057	.070

Lower RMSEA values indicate a better fit. Browne & Cudeck (1992) originally proposed that an RMSEA <= .05 suggested a good fit, while a value above .1 suggested a serious problem, though thresholds are not necessarily useful (Chen et al., 2008). CFI varies between 0 and 1 and compares the fit of the test and null models, with higher values implying a better fit. Finally, lower SRMR values also signal better fits. Hu & Bentler (1999) suggest combined thresholds of CFI >= .95 and SRMR <= .08 for acceptable fit, though these do not seem to be robust (Fan & Sivo, 2005). Based on these measures of global fit, the subscale model is the best-fitting model. Loadings for all models can be found in Appendix 8.4.

GSQ Item Selection

As the subscale model was found to be the best fitting model, it was decided that the short-form version of the GSQ should use the item in each subscale with the highest loading onto its subscale's latent variable, implying the greatest measurement of the underlying phenomena. This led to the items listed in Appendix 8.1. Out of interest, the same process was completed with the other candidate models as well, which led to the same items.

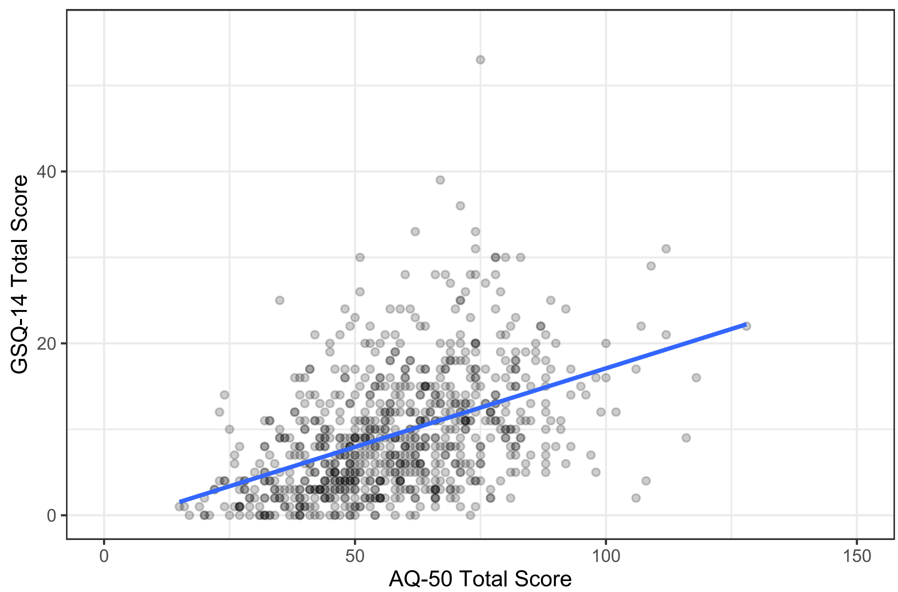
Calibration sample

The internal reliability of the new 14 questions of the Glasgow Sensory Questionnaire (GSQ-14) was assessed using the standardised Cronbach's alpha and Revelle's Omega total, both of which were found to be 0.84.

Total scores on the GSQ-14 were heavily skewed, so Spearman's rank correlation was used to assess the correlation between GSQ-14 and AQ. This correlation was significant (ρ (785) = 0.49, $p < .001$) and can be seen in Figure 3.2.

Figure 3.2

Scatterplot of relationship between total scores on AQ-50 and GSQ-14 of calibration sample. The blue line shows regression line.

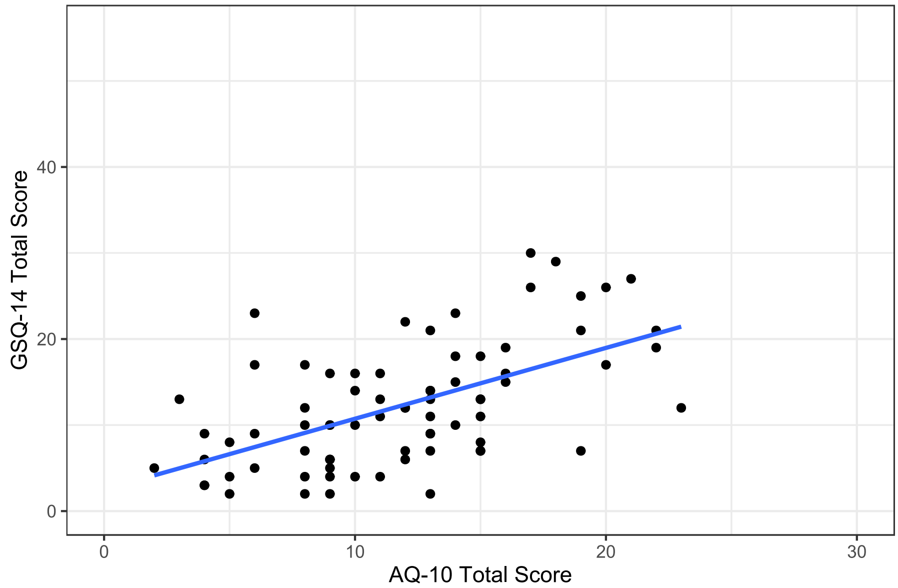


3.5.2 Validation Analyses

The standardised Cronbach's alpha of the GSQ-14 was found to be 0.83, compared to an alpha of 0.79 for the AQ-10. Revelle's omega total estimates for both questionnaires were similar, with an estimate of 0.84 for the GSQ-14 and 0.80 for the AQ-10. The correlation between AQ-10 and GSQ-14 scores was again assessed using Spearman's rank correlation and was found to be statistically significant (ρ (74) = 0.59, $p < .001$).

Figure 3.3

Scatterplot of relationship between total scores on AQ-10 and GSQ-14 of validation sample. The blue line shows regression line.



3.6 Discussion

The current study reports the development and validation of the Glasgow Sensory Questionnaire Short (GSQ-14). This questionnaire is a measure of sensory reactivity commonly experienced by autistic people. After identifying a question from each combination of modality and sensitivity from the original GSQ, the GSQ-14 was found to have good internal reliability and concurrent validity. This is initial evidence for the GSQ-14 being a feasible measure.

The finding that more sensory processing differences are present with greater levels of autistic traits is in line with the body of research using multiple questionnaires, as well as in the general population and autistic population (Horder et al., 2014; A. E. Robertson & Simmons, 2013; Tavassoli et al., 2014). The strength of this relationship is also like those of previous studies, indicating that using the shorter version of the GSQ should not remarkably decrease its effectiveness or its power when used with statistical tests.

The findings from the confirmatory factor analyses provide some interesting insights. While the models are not perfect, they imply that while sensory reactivity differences increase across all modalities and directions together, some items move more closely to each other than others. In particular, this seems to apply to the subscales originally identified by Robertson & Simmons (2013). This finding aligns with previous efforts using confirmatory factor analysis including Weiland et al. (2020) who found a good global fit for a hierarchical model where the items of the Sensory Perception Quotient Short loaded onto factors representing the senses which further loaded onto a general sensory sensitivity factor. Similar results were also found by Williams et al. (2023) when using the Sensory Profile and Sensory Experiences Questionnaire.

This hierarchical structure aligns with qualitative reports (Landon et al., 2016) and supports several of the theories explaining sensory sensitivities and reactivity (Baum et al., 2015; Ward, 2018). For example, the excitation-inhibition imbalance (Rubenstein & Merzenich, 2003), neural noise (Simmons, 2019), and Bayesian (Pellicano & Burr, 2012; van de Cruys et al., 2014) models describe mechanisms which apply equally across all processing networks within the brain. Any differences, therefore, affect all modalities to similar degrees. However, each modality will also have their own complexities. To provide an example, variance is an intrinsic element of smell that is contingent upon the binding of odorants with their complementary receptors. Conversely, the sensation of temperature has relatively little noise. According to the principles of neural noise and Bayesian priors, these differences would result in varying experiences for an individual across their modalities.

3.6.1 Limitations and Future Directions

For the purposes of this initial study, only the AQ was used as a measure of concurrent validity. While this was suitable to judge whether the GSQ-14 was still associated with autism and autistic traits, it is not certain that measure behaves similarly when compared to other measures of sensory processing. For this reason, future work will look to collect a new sample of participants to inspect the internal functioning of the questionnaire alongside another similar sensory questionnaire, such as the Sensory Perception Quotient Short (Tavassoli et al., 2014). A similar concern is that both the Glasgow Sensory Questionnaire and its short version were developed on general population samples (A. E. Robertson & Simmons, 2013) and the performance of these measures have not been rigoursly tested on autistic people to ensure that response patterns remain consistent. The test-retest reliability for the questionnaires has also not yet been assessed. These points limit the inferred validity of the measure among the autistic population and limits the utility of the measures in the clinical setting. Future work should be conducted to assess the long-term performance and measurement invariance between autistic and non-autistic people of both versions of the Glasgow Sensory Questionnaire to ensure that they perform as expected.

In both the construction and validation sample, women were overrepresented compared to what would be expected from a general population. Given previously identified gender differences in the distributions of autistic traits (Ruzich, Allison, Chakrabarti, et al., 2015; E. Taylor et al., 2020), it would be worthwhile for future research to consider the overrepresentation of women in research samples.

3.6.2 Conclusion

This study provides the construction, initial validation, and first use of the GSQ-14. The GSQ-14 seems to be internally reliable and has concurrent validity, meaning that it could be a useful tool for measuring sensory reactivity. The confirmatory factor analysis used for the construction of the scale has the potential to shed some light on the underlying structure of sensory processing experienced by autistic people, though it has not been fully vetted. The correlation between the GSQ-14 and AQ is another contribution to the large body of literature showing that autistic people can experience a different sensory landscape compared to non-autistic people.

4. Modelling the Relationship between Neurodivergences and Sensory Reactivity

4.1 Abstract

Differences in sensory processing have been identified by researchers across multiple neurodivergences, but the characteristics of each neurodivergence have often been explored individually. As people often identify with more than one neurodivergent condition, it is unclear whether sensory reactivity is related to a single neurodivergence, such as autism, or emerges from a more general ‘neurodiversity’ factor. This study recruited two samples – 123 participants from the general population and 120 participants from the neurodivergent population. These participants completed questionnaires measuring their ADHD, autistic, and dyslexic traits, as well as their sensory reactivity. The two samples were then used to estimate and test five theoretically derived structural equation models. The best fitting of these models found that each of the questionnaires formed their own latent variables, which co-varied with the others. Notably, both ADHD and autistic traits had a strong relationship with sensory reactivity. This finding joins a body of literature identifying the overlap between ADHD and autism, and the looser network of neurodivergent conditions.

4.2 Introduction

The differences of sensory processing between autistic and non-autistic people have been relatively well documented through a combination of experiential reporting and experimentation. There is a consensus that the differences are present across many processing stages (He et al., 2023) and senses (MacLennan, O’Brien, et al., 2021), and can be experienced as both an under- and over- response to sensory input (W. Dunn, 1999). Studies also consistently find that measures of these sensory differences correlate with measures of autistic traits in the general population (Horder et al., 2014), therefore indicating that the Broader Autism Phenotype (Constantino & Todd, 2003) also includes a sensory component. It is for these reasons that most tools which access sensory processing differences tend to be based on the autistic experience (Eeles et al., 2013; Gunderson et al., 2023), including those which are not designed to be autism specific.

The emergence of the neurodiversity movement has led to a greater emphasis on neurological complexity and the similarities between clinically distinct neurodevelopmental conditions (Astle et al., 2022). This reconsideration of the diagnostic boundaries was prompted by the significant heterogeneity that exists within diagnostic groups (Masi et al., 2017) and the overlap between different diagnostic labels. Most notorious of these overlaps is between autism and ADHD with an estimated 38.5% of autistic people also receiving a diagnosis of ADHD (Rong et al., 2021), despite diagnostic manuals only recently allowing for both conditions to be diagnosed concurrently (Rosen et al., 2021). Differences in executive function and attentional processes have been identified as the key source of this overlap (Mansour et al., 2021), though other factors may also be relevant (Antshel & Russo, 2019). There have also been suggestions that the two neurodivergences combine to be expressed in a form that is more than their constituent elements (Craddock, 2024), though the formal research is in its infancy.

Comparable similarities are present between most combinations of neurodevelopmental conditions, such as ADHD and Tourette's syndrome (Cravedi et al., 2017), ADHD and dyslexia (Peterson & Pennington, 2015), or dyslexia and dyscalculia (Landerl & Moll, 2010). These factors have led for calls to use a more dimensional approach in research with neurodivergent populations (Dwyer, 2022), not dissimilar to calls in psychiatry as a whole (Dalgleish et al., 2020). This approach would not discard diagnostic categories, but combine them with other measures.

Sensory processing differences are one of the potential dimensions which cross diagnostic boundaries. This is particularly the case for people with ADHD, where differences are present across all the same senses as in autistic people and are expressed similarly (Ghanizadeh, 2011; Panagiotidi et al., 2018). Given the diagnostic overlap between autism and ADHD, as well as the similarities in sensory processing differences, it is unsurprising that several studies have attempted to disentangle the two. In one of these, Cheung & Siu (2009) found no significant difference in Sensory Profile scores between autistic children and children with ADHD. Meanwhile, Dellapiazza et al. (2021) found that not only were autistic children and children with ADHD largely statistically indistinguishable, children with *both* ADHD and autism had the most atypical scores on the auditory and multisensory sections. Using a network analysis of different questionnaire subscales, Varbanov et al. (2023) found that autistic, ADHD, anxious, and schizotypal traits were clustered together in two communities, while sensory responsivity formed a separate, but positively related, cluster. Qualitative work has also identified both similarities and differences in the experience of perceptual capacity and sensory attention between autism and ADHD (Irvine et al., 2024). Considered as a whole, these results imply a complex interconnectedness between ADHD, autism, and sensory processing.

Dyslexia is another neurodivergent condition where sensory processing differences are a topic of research interest, especially as an area of diagnostic overlap (Wright & Conlon, 2009). Differences have been noted in the processing and attentional direction of auditory and visual inputs (Perrachione et al., 2016; Zoubrinetzky et al., 2014), which are then applied to oral and visual communication. There is some debate whether these differences are a cause of dyslexic traits or the result of subsequent reduced reading practice (Goswami, 2015), though there is likely an element of truth in both accounts (O'Brien & Yeatman, 2021). In a regression analysis, Brimo et al. (2021) found that several subscales associated with autism *and* autistic perception independently predicted dyslexic difficulties. Similar to ADHD, this finding would be consistent with dyslexia having its own relationship with sensory processing difficulties associated with autism, alongside autistic traits.

In a recently released pre-print, Apperly et al. (2023) looked to apply a trans-diagnostic approach to different neurodivergent conditions. They did this by asking 995 participants to complete self-assessments of traits associated with ADHD, autism, dyslexia, dyspraxia, sub-clinical epilepsy, tic disorders, and sensory reactivity. The authors then tested a series of different confirmatory factor analysis models on their data before arriving at a single well-fitting model. This model comprised one general 'neurodiversity' factor loading onto every subscale, including sensory reactivity, and four domain specific factors. If this finding is a meaningful representation of reality, it should be possible to predict levels of sensory reactivity using a combination of neurodivergent traits.

The aim of this study will be to replicate the findings of Apperly et al. (2023) using a smaller number of slightly different questionnaires - chosen given their previous associations with sensory processing differences. From a trans-diagnostic perspective, it would be expected that the best fitting model should contain a second-order factor representing 'neurodiversity' that covers all items. Similarly, if sensory processing differences are not unique to autism or autistic traits, the domain-specific factors should also have a relationship with sensory reactivity, potentially through the neurodiversity factor.

4.3 Methods

4.3.1 Measures

Abbreviated Adult Reading History Questionnaire

The Abbreviated Adult Reading History Questionnaire (ARHQ-Brief; Feng et al., 2022) is a shortened version of the Adult Reading History Questionnaire (Lefly & Pennington, 2000). The ARHQ-Brief consists of 6 questions related to childhood reading, reversal, and spelling skills. Each item asks the participant to respond on a 5 point Likert scale, scoring between 0 and 4, though the answer prompts vary between items. The maximum score a person can achieve is 24, and a score above 8 indicates the completer is dyslexic.

Adult ADHD Self-Report Screening Scale for DSM-5

The Adult ADHD Self Report Scale (ASRS-5; Ustun et al., 2017) is a self-administered questionnaire for adults used to assess whether someone would be likely to receive a diagnosis of ADHD. The version used in this data collection has been updated to conform to the criteria introduced in the DSM-5, which reduced the symptom number and early onset requirements (APA, 2022; Kessler et al., 2005). The screening edition of the ASRS-5 comprises 6 statements asking participants to indicate the frequency with which they experience signifiers of ADHD. Participants do this using a 5-point Likert scale ranging from 0 (Never) to 4 (Very Often). Ustun et al. (2017) determined a score of over 14 to be a reasonable cause for further diagnostic assessment for ADHD.

Autism Spectrum Quotient Short

The Autism Spectrum Quotient Short (AQ-10; Allison et al., 2012) is a 10 item revision of the Autism Spectrum Quotient (Baron-Cohen et al., 2001), designed to offer a brief assessment of an individual's levels of autistic traits. The questionnaire is split into 5 subscales measuring social skills, attention switching, attention to detail, communication, and imagination. Each subscale contains two items from the original questionnaire. Participants are asked to signal the extent to which they agree with each item on a 4 point Likert scale from Definitely Disagree to Definitely Agree. In this study, responses were scored between 0 and 3 in line with recommendations from Auyeung et al. (2008), leading to potential scores ranging from 0 to 30. In a clinical setting, individuals who endorse over 6 items are recommended for diagnostic assessment (Allison et al., 2012).

Glasgow Sensory Questionnaire Short

The Glasgow Sensory Questionnaire Short (GSQ-14) is a shortened version of the original Glasgow Sensory Questionnaire (A. E. Robertson & Simmons, 2013) developed in chapter 3 of this thesis. These scales aim to capture affective sensory reactivity associated with autistic people. The questionnaire uses a single item from each of the 14 subscales in the long version, covering seven different senses - vision, audition, olfaction, gustation, tactile, proprioception, and the vestibular sense – and whether the individual is hyper- or hypo-reactive to each. Participants responded to each item using a 5-point Likert scale ranging between 0 (Never) and 4 (Always). Scores on the GSQ-14 are therefore limited between 0 and 56.

4.3.2 Participants

General Population Sample

Data were collected from 123 participants using an online questionnaire on the *Experimentum* platform hosted by the School of Psychology and Neuroscience at the University of Glasgow (DeBruine et al., 2020). Participants were recruited using the University of Glasgow participant pool. Inclusion criteria required that participants be English-speaking adults capable of providing their informed consent. Based on these criteria, it was presumed that the participants would mirror the overall population in terms of composition, meaning that there would be some neurodivergent individuals present, but they would not constitute a majority of the sample.

Participants did not receive compensation for their time. All participants completed the AQ-10, ARHQ-Brief, ASRS-5, and GSQ-14, as well as small number of demographic questions. Within the sample, 69 participants were women, 30 were men, 21 were non-binary or genderqueer, and 3 participants identified as another gender. Participant ages ranged between 18 and 70 (M = 29.80, SD = 9.89). Ethnicity and socioeconomic data were not recorded from participants.

Neurodivergent Population Sample

The structural equation models used in the analyses were used as the basis for a power analysis. The degrees of freedom were set as 630, alpha was 0.05, and the desired power was 0.90. Based on these parameters, it was estimated that the number of participants required to test the close fit of the models would be 73 (K. H. Kim, 2005). The eventual participant recruitment target was set to 120 as the maximum given budgetary constraints.

120 participants were then recruited using the *Profilic* platform (*Prolific*, 2023) and completed the study on *Qualtrics* (*Qualtrics*, 2005). Inclusion criteria were that participants be English-speaking adults in the UK capable of providing their own consent and self-identify as neurodivergent. Participants were not offered a definition of neurodivergence or neurodiversity as to prevent researcher preconceptions influencing the results. Participants were paid £1.20 for ~8 minutes of their time. All participants completed the AQ-10, ARHQ-Brief, ASRS-5, and GSQ-14, as well as a short series of demographic questions. Responses were screened to ensure that they were genuine, but none were excluded. Within the sample, 79 participants were women, 38 were men, and 3 were non-binary or genderqueer. The mean participant age was 38.28 (SD = 12.89), ranging between 19 and 79. Education, ethnicity, and self-identified neurodivergent characteristics of the sample can be found in Tables 4.1, 4.2, and 4.3.

Table 4.1

Ethnicity Characteristics of the Neurodivergent Sample

Ethnicity	N
White	111
Black/African/Caribbean	3
Mixed, two or more ethnic groups	3
Asian (Indian, Pakistani, Bangladeshi, Chinese, any other Asian background)	2
Other (Arab or any others)	1

Table 4.2

Highest Level of Education Achieved in Neurodivergent Sample

Education Level	N
Some secondary	6
Completed secondary school	19
Vocational or similar	13
Some university but no degree	16
University bachelor's degree	47
Graduate or professional degree (M.A., MS, MBA, PhD, JD, MD, DDS)	19

Table 4.3

Self-identified Neurodivergences in Neurodivergent Sample

Neurodivergence	N
ADHD	60
Autism	51
Dyslexia	15
Dyspraxia	12
Dyscalculia	10
Other	9
None	14

Note. Participants had the option to select more than one neurodivergence, meaning that the values in this table sum to greater than 120.

4.4 Data Analysis

4.4.1 Theoretical Underlying Structure

The underlying data structures in this study were based on those tested by Apperly et al. (2023). While the present study used only a subset of those collected by Apperly et al. (2023), the models themselves were not drastically changed. Two further models were tested, based on the wider literature. The first of these regressed autistic traits onto sensory reactivity and did not allow sensory reactivity to co-vary with ADHD or dyslexic traits. This model would test the theory that sensory reactivity arises solely as an output of autistic traits which other neurodivergences correlate with, as implied by autism-first questionnaires (Gunderson et al., 2023). To contrast, the second additional model regressed ADHD, autistic, and dyslexic traits onto sensory reactivity, which would represent each trait having their own direct sensory processing effects, as inferred from by studies considering multiple conditions (Brimo et al., 2021; Varbanov et al., 2023).

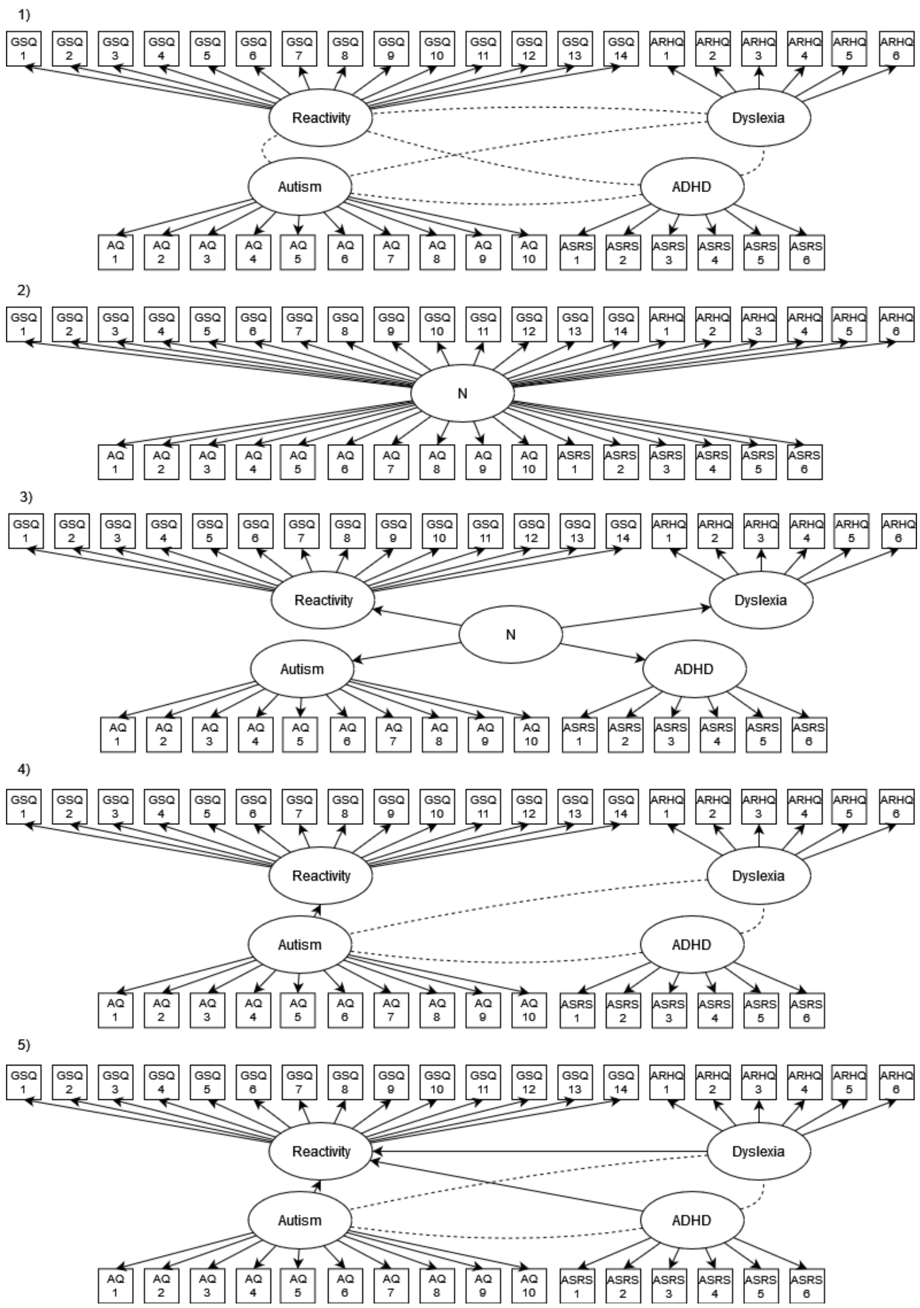
4.4.2 Model Specification

Seven structural equation models were initially tested, each of which had a theoretical basis for representing the different relationships between behaviours characteristic of neurodivergent conditions. In the first and simplest model, the items of each questionnaire were loaded onto different latent factors which were allowed to correlate with each other. For the second model, all items were instead loaded onto a single 'N' factor, representing a general neurodivergence factor. For the third model, the latent factors in model 1 were used and then loaded onto a second order 'N' factor. The fourth model again used each of the questionnaires as latent variables, however, only autism was used as a predictor of sensory reactivity. In the fifth and final model, the ADHD, autism, and dyslexia latent variables were set as predictors of sensory reactivity. These models are visualised in Figure 4.1.

The best fitting model tested by Apperly et al. (2023) involved having each questionnaire item load onto two latent variables: its questionnaire *and* an 'N' factor at the same time. It was attempted to replicate this model using the present data, however, the model could not be identified. This failure to identify the model is likely the result of its complexity, which Apperly et al. (2023) compensated for by using subscale scores as the measured variables, rather than the items themselves.

Figure 4.1

Different potential latent structures tested in this study. Squares represent questionnaire items and circles represent latent factors. Solid arrows indicate a directional relationship and dashed lines indicate covariance. 1) Each questionnaire forms a latent variable which freely covary with each other. 2) All questionnaire items load onto a single 'neurodiversity' factor. 3) Each questionnaire forms a latent variable and those variables are derived from an underlying 'neurodiversity' factor. 4) An 'autism-first' model where each questionnaire forms a latent variable and the neurodivergent conditions covary with each other, but only autism affects the sensory reactivity latent variable. 5) Each questionnaire forms a latent factor, the neurodivergent conditions covary with each other, and each neurodivergent condition affects sensory reactivity.



4.4.3 Analytical Decisions

All models were estimated using version 0.6-11 of the *lavaan* package in R version 4.2.3 (R Core Team, 2013; Rosseel, 2012). As all items in the questionnaires were scored on a Likert scale, it was felt to be appropriate to treat each as an ordinal variable. For this reason, the models used covariance matrices and diagonally weighted least squares as the estimation method. Given this choice, the data were not transformed before the analysis. Any participants with missing data were excluded from the analysis.

For the structural equation model analyses, the two samples were combined. To account for the different population types, they were coded as being two different groups, allowing for slightly different estimates. For this analysis to function, any responses to items should be present in both groups. However, this was not the case for questions 6, 7, and 14 in the GSQ-14 and question 3 of the ARHQ-Brief. To work around this issue, the high-scoring participant's response was reduced from 4 to 3, which had only a trivial effect on the overall results.

4.5 Results

4.5.1 General Population Sample Analyses

The descriptive statistics and internal consistency measures for the questionnaires in the general population sample can be found in Table 4.4. The ARHQ-Brief and ASRS-5 had alpha and omega coefficients below the .7 threshold which is considered to be acceptable (Cortina, 1993), suggesting that they were imperfect for measuring a single concept.

Table 4.4

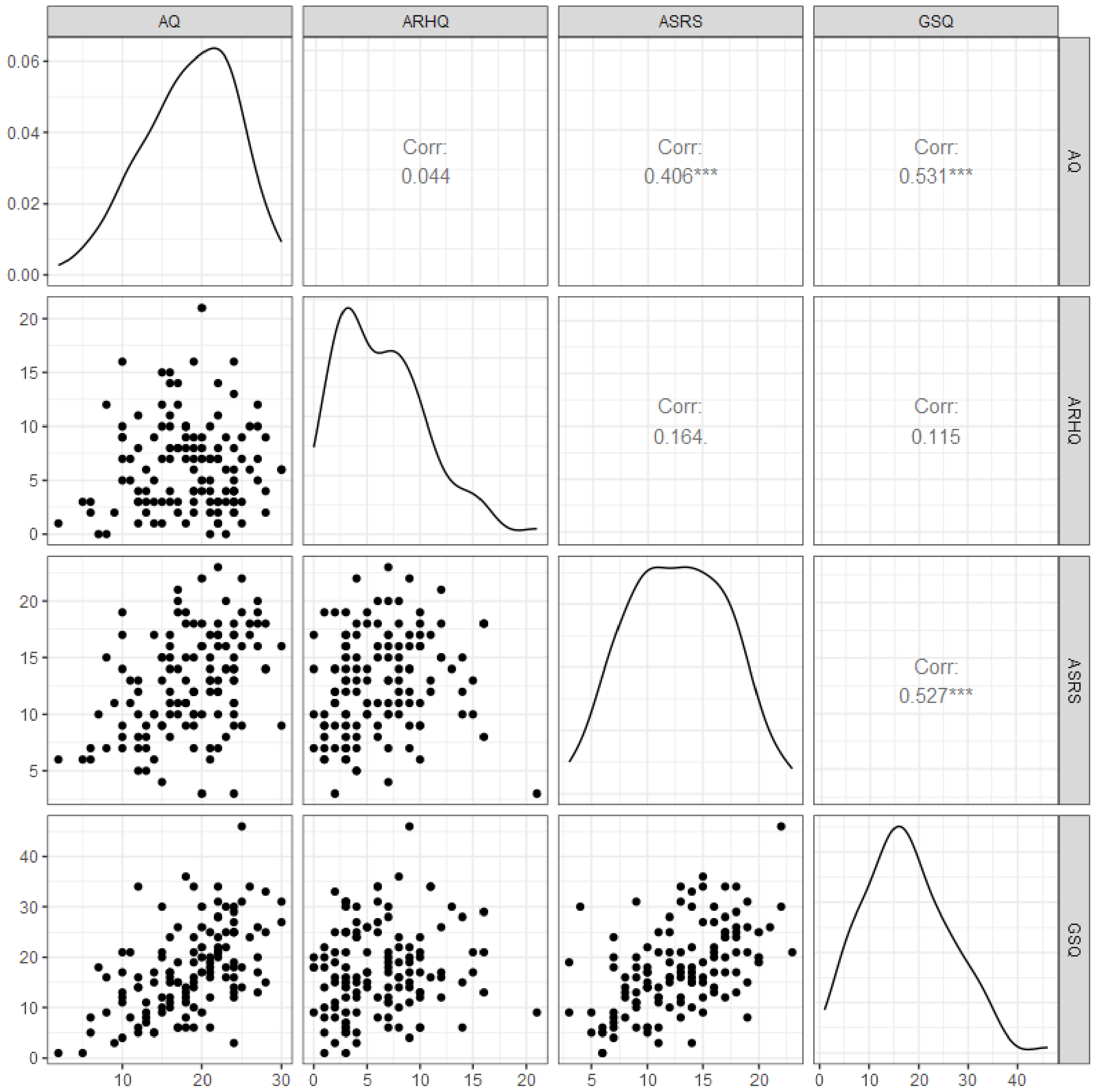
Questionnaire Descriptives for General Population Sample

Questionnaire	Mean	SD	Cronbach's Alpha	Revelle's Omega
AQ	18.45	5.82	.82	.82
ARHQ	6.31	4.18	.66	.67
ASRS	12.73	4.48	.69	.70
GSQ	17.50	8.66	.83	.83

The distributions and correlations between the scores of the different questionnaires can be seen in Figure 4.2. Each of the questionnaires formed approximately normal distributions, albeit with some skew in both directions. When adjusted for multiple comparisons using the Benjamini-Hochberg method (Benjamini & Hochberg, 1995), the AQ-10 was found to correlate with the ASRS-5 ($r(123) = .41$, $p < .001$) and GSQ-14 (r(123) = .53, p <.001). The GSQ-14 was also significantly correlated with the ASRS-5 (r(123) = .53, p<.001). Correlations between the ARHQ-Brief and AQ-10 (r(123) = 0.04, p = .64), ASRS-5 (r(123) = .16, p = .11), and GSQ-14 (r(123) = .12, p =.25) were not significant.

Figure 4.2

Scatterplots, density plots, and Pearson correlation coefficients of and between total scores on the Autism Spectrum Quotient Short (AQ), Adult Reading History Questionnaire Brief (ARHQ), Adult ADHD Self-Report Screening Scale for DSM-5 (ASRS), and Glasgow Sensory Questionnaire Short (GSQ) in the General Population Sample.



Note. *** indicates an unadjusted p-value of below .001.

4.5.2 Neurodivergent Sample Analyses

The questionnaire descriptives for the neurodivergent sample can again be found in Table 4.5. Compared to the general population sample, the ARHQ-Brief and ASRS-5 had much higher coefficients of internal consistency, likely as a consequence of their foundation as diagnostic screening tools. The distributions of questionnaire scores, as visualised in Figure 4.3, are also broadly similar, forming normal distributions. Even when using the Benjamini-Hochberg correction (Benjamini & Hochberg, 1995), the ASRS-5 was significantly correlated with all other questionnaires, including the AQ-10 ($r(118) = .33$, $p < .001$), ARHQ-Brief ($r(118) = .23$, $p = .01$), and GSQ-14 ($r(116) = .52$, $p = <.001$). The GSQ was also significantly correlated with both the AQ-10 ($r(118) = .42$, $p <.001$), and ARHQ-Brief ($r(118) = .26$, $p = .007$). The only non-significant correlation was between the AQ-10 and ARHQ-Brief ($r(120) = .07$, $p = .44$). Questionnaire scores by self-identified neurodivergence can also be found in Figure 4.4.

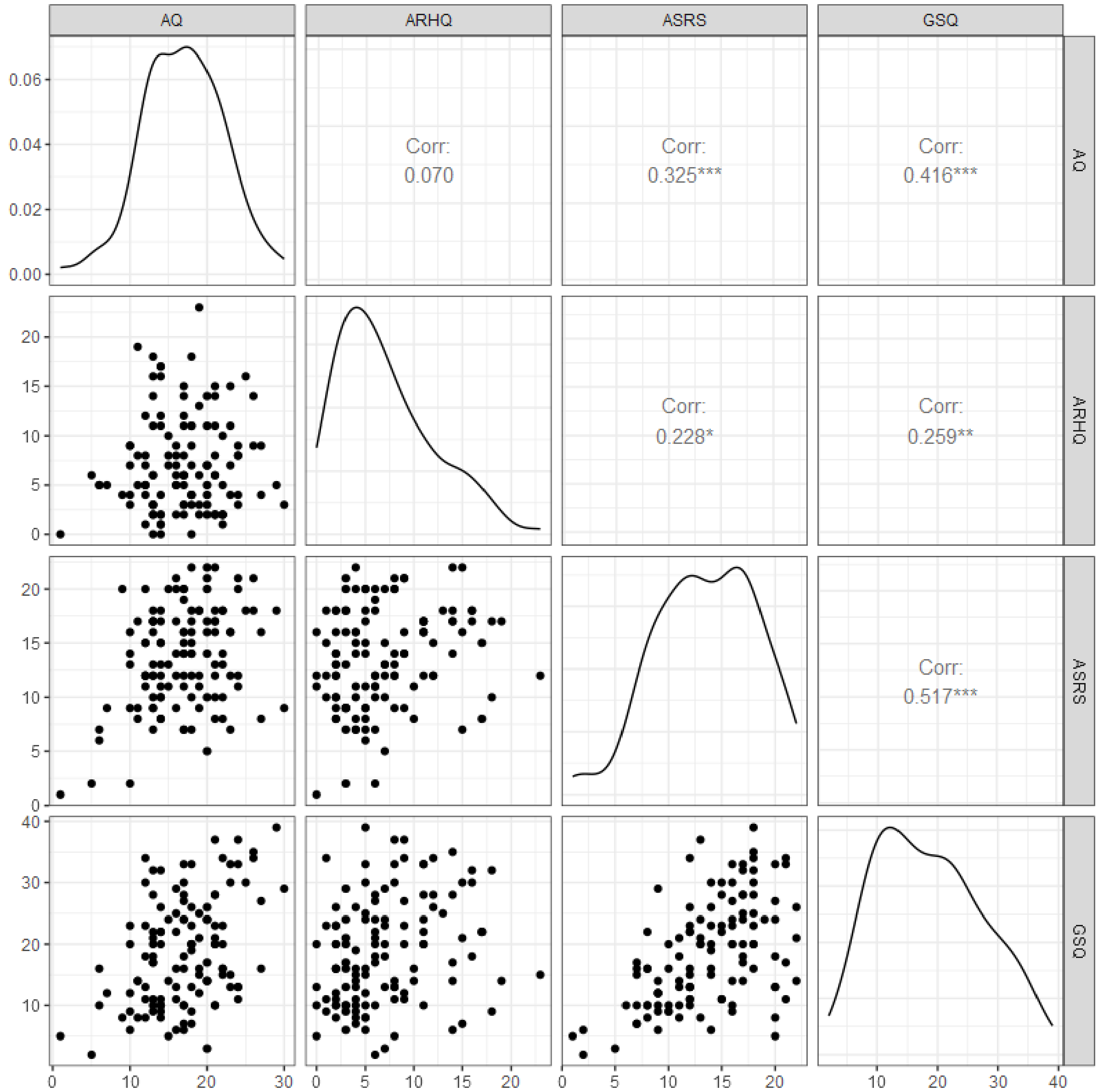
Table 4.5

Questionnaire Characteristics for Neurodivergent Sample

Questionnaire	Mean	SD	Cronbach's Alpha	Revelle's Omega
AQ-10	16.92	5.16	.76	.78
ARHQ-Brief	7.03	4.88	.78	.79
ASRS-5	13.62	4.65	.75	.75
GSQ-14	18.72	8.76	.83	.83

Figure 4.3

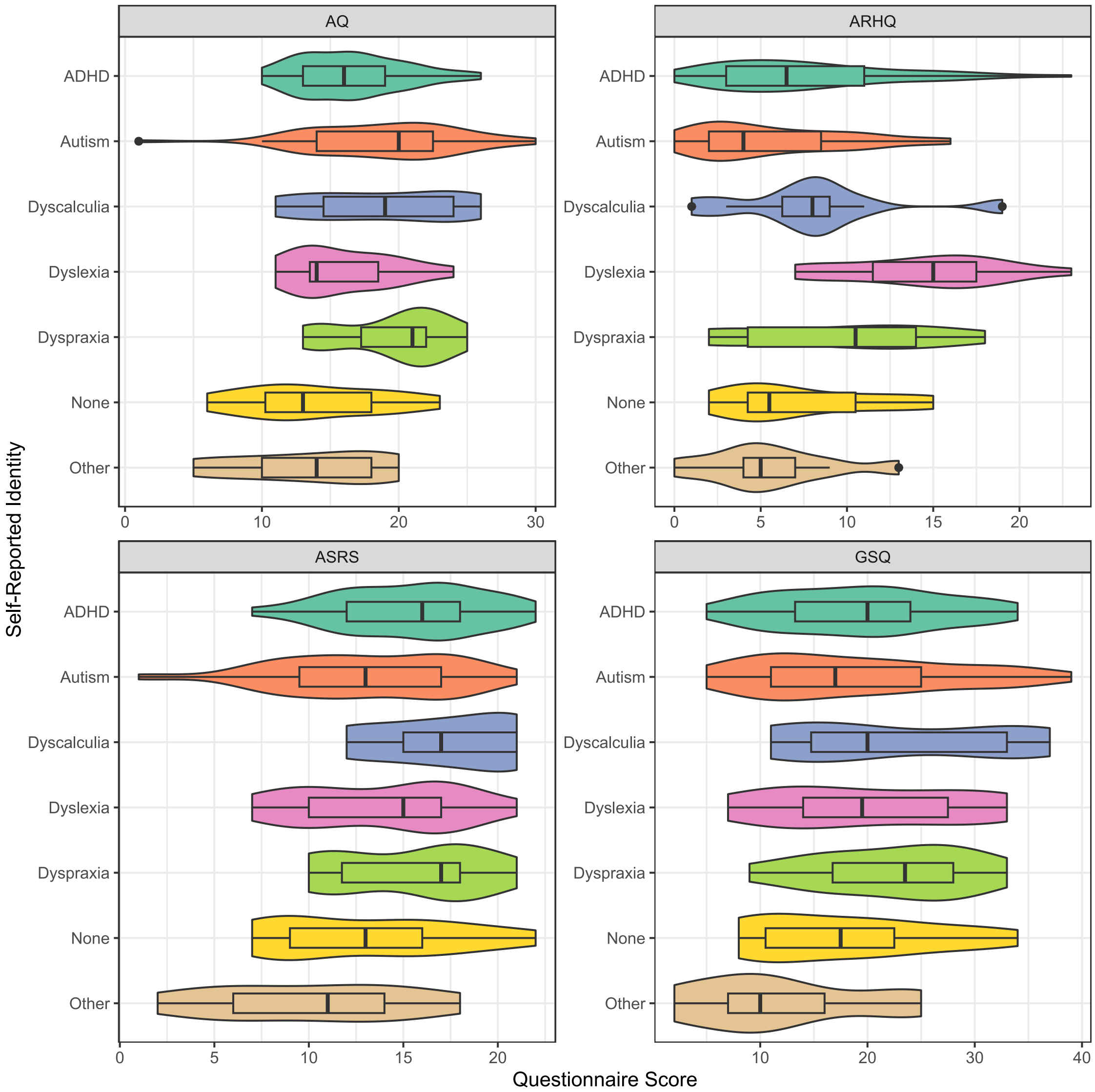
Scatterplots, density plots, and Pearson correlation coefficients of and between total scores on the Autism Spectrum Quotient Short (AQ), Adult Reading History Questionnaire Brief (ARHQ), Adult ADHD Self-Report Screening Scale for DSM-5 (ASRS), and Glasgow Sensory Questionnaire Short (GSQ) in the neurodivergent sample.



Note. All p-values are unadjusted. * = p < .05, ** = p < .01, *** = p < .001.

Figure 4.4

Violin plots and boxplots for distributions of total scores on the Autism Spectrum Quotient Short (AQ), Adult Reading History Questionnaire Brief (ARHQ), Adult ADHD Self-Report Screening Scale for DSM-5 (ASRS), and Glasgow Sensory Questionnaire Short (GSQ) by self-identified neurodivergence in the neurodivergent sample. Each black dot indicates an outlier. Bold lines show median scores and boxes show interquartile ranges. Box whiskers represent the largest of the total range of the data or 1.5 times the interquartile range.



4.5.3 Combined Sample Structural Equation Models

243 participants were used to estimate five models which were successfully identified. The indices of global fit for these models can be found in Table 4.6. Models 1 and 5, where each questionnaire was represented by a latent variable and allowed to either correlate or regress on each other, had the same and best fit according to all global measures of the tested models and were therefore selected. These fits were

acceptable, though not outstanding. RMSEA values of below .05 are generally considered to be good, while values below .01 are acceptable (Browne & Cudeck, 1992). A good fitting model may also have CFI values above .95 and SRMR values below .08 (L. Hu & Bentler, 1999). Even considering the caveats of fit thresholds (Fan & Sivo, 2005), these models are likely an acceptable, but not the best possible, representation of the data that has been collected. It should be noted that the individual parameter estimates for the relationships between the latent variables differed. The significant chi-square tests suggested that there were issues of local fit and this was confirmed upon inspection of the residuals, however, the researcher could not identify a theoretical explanation for these differences.

Table 4.6

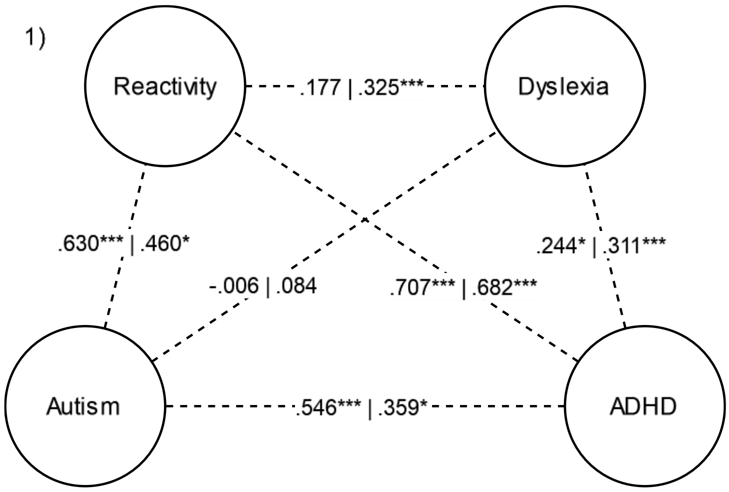
Model Indices for Potential Structural Equation Models

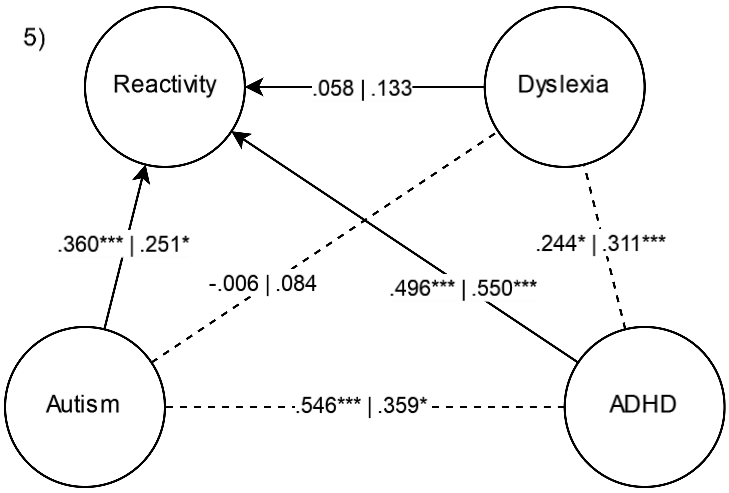
Model	Chi-square	Degrees of Freedom	P-value	CFI	RMSEA	SRMR
Model 1 & 5	1954.5	1176	<.001	.925	.075	.119
Model 3	1980.8	1180	<.001	.923	.076	.120
Model 4	2309.3	1180	<.001	.891	.090	.128
Model 2	3278.7	1180	<.001	.799	.122	.142

A simplified illustration of the estimated relationships from models 1 and 5 are visualised in Figure 4.5. For full model characteristics, please refer to the analytical materials in appendix 8.3. In both models, all latent variables are positively associated with each other, such that a rise in one is likely to be accompanied by a rise in another. Also in both models, the observed covariances varied between the two samples. When the directionality between reactivity and the neurodivergent latent variables is specified, the estimates were more stable between the two samples. In both models and both samples, it is apparent that both autistic and ADHD traits independently predict higher sensory reactivity.

Figure 4.5

Visualisation of best fitting structural equation models. Dashed lines symbolise correlations and arrows symbolise standardised regressions. Values on the left are estimates from the general population group, while values on the right are estimated using the neurodivergent group.





Note. * indicates p < .05, *** indicates p < .001.

4.6 Discussion

This chapter describes an analysis of several questionnaires which aim to capture traits associated with ADHD, autism, and dyslexia, as well as sensory reactivity. Two separate samples were collected for this study, one of which was recruited from the general population and another from people who identified as neurodivergent. The correlations between the questionnaires in both samples were calculated. In both groups, autistic and ADHD traits and sensory processing scores were found to be significantly correlated. In the neurodivergent sample, but not the general population sample, dyslexic traits were found to correlate with ADHD and sensory processing scores.

Several theory-based structural equation models were then tested and assessed for their fit to the data. While no models could be described as perfect, two similar models were identified as having an adequate fit. These models used the items from each of the questionnaires as separate latent variables which co-varied with each other. For one model, they were defined as non-directional correlations. For the second model, the ADHD, autism, and dyslexia latent variables regressed onto the sensory reactivity latent variable.

The strong correlations between some of the different measures of neurodivergence and sensory reactivity were the expected results from previous research. This includes similar studies looking at the correlations between autism and ADHD (Varbanov et al., 2023), ADHD and dyslexia (Bergen et al., 2023), and each with sensory reactivity (Brimo et al., 2021; Horder et al., 2014; Panagiotidi et al., 2018). It was therefore initially surprising that dyslexia had only small correlations with the other measures, to the point that they were not significantly above zero in the general population sample. However, in a correlational analysis of multiple neurodivergent questionnaire subscales, Apperly et al. (2023) also found low or non-significant correlations between their dyslexia subscales and the subscales representing autism and ADHD. Notably, their correlations between the dyslexic subscales and sensory reactivity were much higher. The present study therefore appears to reproduce this result, which was examined further in the model analyses.

While this study aimed to replicate the model found by Apperly et al. (2023) to have the best fit to their data, it could not be tested because the model was too complex to be identified. Additionally, both models using a general 'neurodiversity' factor were found to fit the data less well than the models where the latent variables were allowed to independently co-vary. These findings therefore appear to present evidence against the use of a trans-diagnostic approach to neurodivergence, as had been advocated for (Dalgleish et al., 2020; Dwyer, 2022). However, this may have resulted from the questionnaires and neurodivergences chosen for the two studies. Dyslexia in particular may emerge from different, though still related, phenomena given the high specificity shown by the ARHQ in this data. By including more questionnaires, Apperly et al. (2023) may have better captured an underlying neurodivergence phenomenon. However, shared loadings on independent factors may not be the best model of neurodivergence when some neurodivergences/traits, such as ADHD and autism, have stronger relationships with each other than other neurodivergences. A wider study using network analyses, like those employed by Varbanov et al. (2023), may be crucial in identifying where different neurodivergent traits cluster together.

Examination of the parameter estimates of the best fitting models also offers some insight. First, the covariance between autism and dyslexia directly is near zero in both models and samples. Similarly, the relationship between sensory reactivity and dyslexia is quite small, except for the covariance in the neurodivergent sample. This would suggest that correlations between dyslexic and autistic traits are nearly entirely accounted for by their shared relationship with ADHD. This may explain why associations between dyslexia, autism, and sensory reactivity have been previously identified (Brimo et al., 2021) while the dyslexia specific sensory phenomena present themselves slightly differently (Perrachione et al., 2016; Zoubrinetzky et al., 2014).

The relationships between autism, ADHD, and sensory reactivity are also interesting. It has been well documented that there is a significant overlap between autism and ADHD, both in terms of co-occurrence and phenomenology (Dellapiazza et al., 2021; Rong et al., 2021). In both samples, a significant correlation was calculated between the autism and ADHD latent variables, though it was smaller in the neurodivergent sample. However, both latent variables had independently strong relationships with sensory reactivity with ADHD traits having a stronger relationship than autistic traits in both the general population and neurodivergent samples. This can only to be attributed to the size of the relationship between ADHD traits and sensory reactivity because the observed correlation between the Autism Spectrum Quotient and Glasgow Sensory Questionnaire were of a similar magnitude to previous studies (Horder et al., 2014). This was especially surprising because the sensory questionnaire used was developed using the experiences of autistic people and did not consider ADHD (A. E. Robertson, 2012).

The relationships between the latent variables for autism, ADHD, and sensory reactivity were also notable for being the source of the greatest difference between the general population and neurodivergent samples. Whereas most other estimates were similar between the two groups, the coefficients between ADHD and autism, and autism to sensory reactivity were lower in the neurodivergent group. The majority of people in the neurodivergent sample were either autistic or had ADHD, which would imply that the relationships are weaker at the higher end of these distributions. There are three possible explanations for this finding. Firstly, it may be that the relationships being modelled are not truly linear but instead exponential, as in commonplace in other psychophysical contexts (Kingdom & Prins, 2016). Secondly, the strong relationships in the general population may be capturing qualitively different experiences between neurotypical and neurodivergent people within the general population group, rather than the dimensional method implied by the methods here (Krakowski et al., 2021). Finally, it is possible that as a consequence of the questionnaires being optimised as screening tools means that they become less sensitive once the diagnostic threshold has been passed. Evidence to choose between these explanations could arise from a combination of further research between diagnostic groups and a larger scale sampling of the general population.

This study was cross-sectional, so the results are not definitive. Yet, it joins a collection of evidence showing that increased ADHD traits predict an increase in sensory reactivity differences (Cheung & Siu, 2009; Dellapiazza et al., 2021). It is possible that this results from a common underlying factor such as anxiety, as was observed by Varbanov et al. (2023), but attempts to model this possibility using the present data either did not fit well or could not be mathematically identified.

4.6.1 Limitations and Future Directions

While the sample which was recruited without a target demographic was labelled as 'general population' throughout this report, this does not necessarily mean that it is a genuine representation of the general population. Instead, the sample appears to contain a higher proportion of high scorers on all questionnaires than would generally be expected (Prasad et al., 2019; Talantseva et al., 2023; Wagner et al., 2020). This is an issue present throughout literature on neurodivergence (Abu-Akel et al., 2019) and is likely the result of neurodivergent people having a greater motivation to participate in research about them. Previous studies using the Glasgow Sensory Questionnaire, for example, have found similar relationships at different levels of autistic traits (A. E. Robertson & Simmons, 2013), but this does not necessarily apply to all neurodivergences and appears contradicted by the comparison between the two samples.

The Glasgow Sensory Questionnaire as a measure was explicitly developed to capture the sensory reactivity experienced by autistic people, though validations have primarily been conducted on general population samples (A. E. Robertson, 2012). It was for this reason that the strong and independent relationship between ADHD traits and Glasgow Sensory Questionnaire was surprising. Equally, this means that the low relationship between dyslexic traits and the Glasgow Sensory Questionnaire does not rule out dyslexia being associated with differences in sensory processing. Instead, those differences may be more specific to dyslexia or a different segment of a neurodivergent constellation. For this reason, this research area could benefit from a holistic exploration of the differing sensory experiences among the neurodivergent population.

A strength of this study was that it identified that the relationships between sensory reactivity and neurodivergences are more complex than simple factor structures. However, the structures identified here may equally be liable to change based on missing variables. For example, while participants were asked to disclose whether they identified with any neurodivergent conditions beyond autism, ADHD, or dyslexia, these identities were not included in the models. Nor were questionnaires assessing these conditions available or completed by participants. Future research could therefore better integrate these into complex analyses to investigate the stability of the relationships shown here with respect to known potential confounders.

4.6.2 Conclusion

Using general population and neurodivergent samples totalling 243 participants, several theoretical models of the relationships between sensory reactivity, ADHD, autism, and dyslexia were tested.

The best fitting models identified separate latent variables for each of the neurodivergences, which varied freely with each other, instead of a single neurodiversity factor. Autism and ADHD were also found to have their own relationships with sensory reactivity. Future research could explore in more detail which sensory processing differences are shared across the neurodivergences and which are unique. In the meantime, research exploring sensory reactivity should consider including both autistic and ADHD traits in their analyses.

5. Measuring the Effect of State Anxiety on Sensory Capacity using Virtual Reality

5.1 Abstract

Several studies have shown that autistic people may have a higher perceptual capacity than non-autistic people. Using the Load Theory of Attention and Cognitive Control, this difference is a plausible explanation for many of the sensory processing differences that have been reported by autistic people. This study aimed to replicate these findings and extend them by using novel virtual reality environments to modulate participants' state anxiety. 48 participants were presented an array of sounds of variable number and then asked to detect which of two targets sounds were played and whether a critical stimulus was also present. The analyses found no effects of the interactions between autistic traits, state anxiety, and perceptual load on the accuracy or reaction times on the primary search task, nor accuracy on the secondary detection task. Potential improvements to the procedure were identified and alternative explanations were discussed.

5.2 Introduction

Research into the perceptual processing of autistic people is mostly inconclusive, with large margins of error and inconsistent findings, though there is an understanding that sensory processing is key to the lived experience and development of autistic people (C. E. Robertson & Baron-Cohen, 2017; Simmons et al., 2009). The allocation of attention is one such stage where differences between autistic people and non-autistic people have been identified, with autistic people finding tasks with distractors more difficult, while also performing better on discrimination tasks (Ames & Fletcher-Watson, 2010).

According to the general load theory of selective attention and cognitive control, the effect of distractor stimuli decreases as the level of perceptual load increases (Lavie et al., 2004). A person has a limited perceptual capacity to process incoming sensory information that is always fully utilised. If the task-relevant perceptual load is equal to the perceptual capacity, only task-relevant information will be processed and forwarded to higher brain areas. However, if the perceptual load is low, task-irrelevant stimuli will also be processed to fill the perceptual capacity. This theory has been tested in behavioural studies, which show that the effect of distractor stimuli decreases as perceptual load increases (Lavie, 2005). These behavioural experiments involve a primary task with increasing levels of distractor stimuli alongside a secondary detection task. If a person has a higher perceptual capacity, their accuracy on the secondary detection task should decrease less than others when more distractors are present, even though their performance on the primary task may be similar.

An increasing body of work seems to demonstrate that autistic people have a higher perceptual capacity in at least the auditory (Remington & Fairnie, 2017) and visual domains (Remington et al., 2009, 2012; Tillmann & Swettenham, 2017). Higher perceptual capacity has also been linked to increased sensory sensitivity measured using the Sensory Perception Quotient (Brinkert & Remington, 2020). Analyses using autistic traits are conflicted, with Bayliss & Kritikos (2011) finding a positive relationship, while Brinkert & Remington (2020) did not.

Studies measuring the neural activity of autistic people when completing attentional tasks also seem to support a load theory account. For example, Dunn et al. (2016) used EEG to find that participants with more autistic traits had more event-related potentials associated with attention shifting, though event-related potentials associated with distractor suppression were reduced. Lau-Zhu et al. (2019) also found that their non-autistic group had increased brain activity with increased perceptual demands, while autistic people had consistent brain activity throughout, implying that their sensory capacity at baseline was already sufficient.

Taking the perceptual capacity approach offers a mechanism for the reported increases in sensory difficulties at higher levels of state anxiety. Perceptual efficiency theory and attentional control theory suggest that anxiety affects the capacities and efficiency of goal-directed and stimulus-driven attentional systems (Shi et al., 2019). Among the predictions of these theories, greater anxiety may lead to a greater exertion of effort, increasing the size of the attentional/perceptual capacity. Autistic people may therefore have a higher perceptual capacity in part because of their trait anxiety, which would then only get larger in times of stress, leading to sensory overwhelm.

The relationship between anxiety and perceptual capacity also appears to be similarly conflicted. Berggren et al. (2015) found that higher levels of trait anxiety were correlated with superior detection of secondary stimuli. As autistic people have higher levels of trait anxiety (Jolliffe et al., 2022), this could be a contributing factor to autistic people's higher perceptual capacity. However, Sadeh & Bredemeier (2011) found that highly anxious people performed worse at higher perceptual loads, suggesting an exactly opposite relationship.

"Virtual Reality" (VR) can describe a wide range of technologies, such as virtual worlds, virtual collaborative environments, cave automatic virtual environments, standalone virtual reality, and head-mounted displays (Newbutt et al., 2019). The connection between these technologies is an immersion in a virtual environment, where immersion is the extent to which the user is displayed an inclusive, vivid, and surrounding illusion of reality (Slater & Wilbur, 1997). The area is constantly advancing, however, currently, the most immersive options are the head-mounted displays where the user has a screen placed in front of each eye, approximating stereoscopic vision (Savickaite et al., 2022). Often, the user can rotate their head and move around in physical space, which is then replicated in the Virtual Space.

There has been some success in using VR as a research and interventional tool with autistic people. VR can offer controllable and predictable sensory environments (Parsons, 2016), which, as previously mentioned, are the most reliable indicators of a safe sensory experience. Most of this research has concentrated on the social aspects of autism, especially social training programs (Miller et al., 2020). A particular area of interest has been the sense of embodiment in avatars, both realistic and not, and how this impacts the effectiveness of communication (Wallace et al., 2017). Unfortunately, the prominence of social interventions is contrary to the interests of the autistic community, who view such efforts as a low priority at best or unnecessary at worst (Roche et al., 2021).

VR has been successfully employed as a safe version of exposure therapy for autistic children with specific phobia in a cave system by Maskey et al. (2014) and expanded by Maskey et al. (2019). Here, virtual environments were developed for each individual to cater to their unique phobia. As they progressed through the program, they were brought closer to the subject of their phobia, before being exposed to the real-life version. The environments were sufficiently immersive that they induced sufficient anxiety in the participants so that they could combat their phobia, demonstrating the power of carefully designed virtual environments.

Despite these developments, challenges remain with the user experience, especially for autistic people. Cyber-sickness is a catch-all term for the negative symptoms that can emerge when using VR, especially those virtual environments with presence, immersion, and movement (Weech et al., 2019). It has been shown that once participants notice cyber-sickness; they are more likely to withdraw from studies (Almeida et al., 2018). The prevalence of cyber-sickness has not been tested in autistic people, however, given the increased sensory processing difficulties and different interpretations of internal bodily cues (Poquérusse et al., 2018), researchers have a duty of care to their autistic participants. There is also the question of how widely VR experiments and interventions can be applied, as current studies have primarily tested on autistic children who have fewer complex needs (Ryan & Newbutt, 2018). As head-mounted displays continue to become more accessible and diffuse through the public, these concerns should reduce. Further, initial work with neurodivergent participants indicates that the experimental experience in VR is often enjoyable (R. Taylor et al., 2023).

The key aim of this study will be to test the hypothesis that both state anxiety and autistic traits affect the size of participants' perceptual capacity, as inferred using a dual-load task, in a general population sample. If successful, this would demonstrate that the primary anxiety model of sensory reactivity has a place to complement the primary sensory over-responsivity model. This will be achieved with a novel research paradigm using Virtual Reality to influence participant state anxiety. As per the prior research described here, there are four key predictions:

1. There will be a positive interaction between autistic traits and perceptual load for accuracy on the secondary detection task.

2. There will be a positive interaction between state anxiety and perceptual load for accuracy on the secondary detection task.

3. There will be a positive three-way interaction between state anxiety, reported autistic traits, and perceptual load for accuracy on the secondary detection task.

4. There will be no effect of autistic traits or state anxiety on reaction time or accuracy on the primary search task.

5.3 Methods

5.3.1 Participants

A simulation-based power analysis was conducted using data from Remington & Fairnie (2017) to estimate a reasonable number of participants. This process found that 17 participants would be sufficient to replicate the critical stimulus analyses from Remington & Fairnie (2017), given the increase in trials per participant. This was set as the minimum target for recruitment. 53 participants were initially recruited for this study using recruitment networks and a direct approach on the University of Glasgow campus. Further recruitment was time limited. Participants were paid £6 for their involvement.

Five participants were excluded from the final analyses. One participant disclosed a hearing impairment during final eligibility checks and four participants were found to have a total accuracy below 60% on the auditory search task. This resulted in 48 participants completing the experiment.

Most heart rate data were missing from 16 participants and eye tracking data was missing from 20 participants because of sensor error. One cause of this issue was identified as smudges from facial makeup covering the sensors. The experimental procedure was adapted to accommodate this issue once identified. These participants were included in analyses that did not require their missing data.

Of the participants included in the final analyses, 29 (55%) were female, 23 (43%) were male, and 1 (2%) participant was non-binary. 35 (66%) participants identified as white, 13 (25%) as Asian, 2 (4%) as mixed race, and 1 (2%) participant identified as each of Arab and black. 1 participant did not provide ethnic information. For the highest level of education completed by the participants, 3 (6%) had completed a diploma or higher apprenticeship, 26 (49%) had completed A-Levels or Highers, 20 (38%) had completed an undergraduate degree, and 4 (8%) had completed a postgraduate degree. Table 5.1 contains summaries of the participants' ages and questionnaires assessing long-term characteristics.

Table 5.1

Descriptive Statistics of Participant Characteristics

Measure	Mean	SD	Range
Age	23.60	6.23	18-50
Autism Spectrum Quotient Short	12.09	5.88	1-31
Glasgow Sensory Questionnaire Short	15.91	10.61	1-42
Trait Anxiety Inventory Short	11.64	3.66	5-20

5.3.2 Ethics

This study was conducted in accordance with the British Psychological Society code of ethics. It was approved by the Medical, Veterinary, and Life Sciences Ethics Committee of the University of Glasgow. All participants completed and signed a statement of informed consent.

5.3.3 Apparatus

The study was conducted using a custom-developed program in Unity Editor version 2021.3.25f1. Participants interacted with the program and had their physiological signals measured using an HP Reverb G2 Omnicept virtual reality headset. While wearing the headset, the participant's heart rate, heart rate variability, and pupil dilation were recorded. The data were collected in two blocks. In the first block, the experiment was performed on a Dell Alienware laptop with an Intel i9 13980HX CPU and Nvidia RTX 4090 GPU. For the second block, a DELL Intel Xeon W-2223 workstation with an Nvidia RTX 3090 GPU was used.

5.3.4 Measures

Autism Spectrum Quotient

The Autism Spectrum Quotient Short (AQ; Allison et al., 2012) was developed from the long-form Autism Spectrum Quotient (Baron-Cohen et al., 2001) to measure an individual's level of autistic traits. The questionnaire contains 10 items split into five subscales: attention switching, attention to detail, communication, imagination, and social skills. Participants use a 4-point Likert scale ranging from *Definitely Disagree* to *Definitely Agree* to respond to each of the items. As suggested by Auyeung et al. (2008), this study scored responses from 0 to 3, rather than the binary scoring used by Baron-Cohen et al. (2001). As a result, scores can vary between 0 and 30. If a participant endorses 6 items, they are likely to be autistic.

Glasgow Sensory Questionnaire Short

The Glasgow Sensory Questionnaire Short (GSQ-14) is a measure designed to capture sensory processing differences experienced by autistic people and was developed in Chapter 3 and based on the questionnaire developed by Robertson & Simmons (2013). It does this by asking about the frequency of sensory behaviours and, therefore, largely captures sensory reactivity. The items are categorised by reactivity direction (hyper- and hypo-sensitivity) and modality (audition, gustation, olfaction, proprioception, tactility, vision, and the vestibular sense). This leads to 14 subscales, each containing a single item. Items are scored on a 5-point Likert scale ranging from 0 (*Never)* to 4 (*Always)*. Participants can score between 0 and 56.

Short Version of Spielberger State-Trait Anxiety Inventory

The Spielberger State-Trait Anxiety Inventory (Spielberger, 1970) is a well-used measure of state and trait non-clinical anxiety. Zsido et al. (2020) subsequently constructed a shortened version of the inventory containing 5 items for each of the state (STAI-S) and trait (STAI-T) scales. Participants mark their agreement with the items using a 4-point Likert scale ranging from 1 (*Not all*) to 4 (*Very much so*). Zsido et al. (2020) suggested cut-offs of 10 for the state scale and 14 for the trait scale, such that if the participant scored at or above the cut-off, they could be considered clinically anxious.

5.3.5 Procedure

This experiment adapted a dual-task paradigm developed by Fairnie et al. (2016). The primary task was an auditory search task, and the secondary task was an auditory detection task. For the primary task, participants were presented with a variable number of animal sounds, distributed in the virtual space in a semi-circle around their head position. Participants were asked to identify which target stimulus was played (either a dog's bark or a lion's roar) alongside the non-target stimuli (chicken, cockerel, cow, crow, or duck). In each trial, the target stimulus was accompanied by either 0, 1, 3, or 5 non-target stimuli. For the secondary task, in half of the trials, participants were presented with the critical stimulus (a car driving past) and were asked whether they had detected the critical stimulus. All sounds had a duration of 100ms and had a 10ms fade in and fade out. Stimuli were presented at ~70 dB. The spectral properties of all stimuli can be found in Table 8.2. Participants registered their responses using either the trigger or grip button on the relevant VR controller. Participants were visually prompted about the relevant questions and responses. Reaction time from stimulus presentation to initial response, the responses themselves, and physiological data were automatically recorded by the program.

Participants were first given the information sheet and given the opportunity to ask questions of the researcher before giving their consent to participate. They were then invited to complete the Autism

Spectrum Quotient, the Glasgow Sensory Questionnaire, the Short State-Trait Anxiety Inventory, and a series of demographic questions. Upon completion of the questionnaires, the participants were taken into the main experimental room where they were introduced and instructed on how to use the Virtual Reality equipment and how to complete the experimental task in a neutral virtual environment. As part of this, the participants completed a training block of the experimental task. Once the participants felt confident and comfortable, they moved into the main section of the experiment.

The experiment was split into three blocks. For each block, participants entered a different virtual environment developed for this experiment to elicit a different level of anxiety. These environments were a low-polygon village (training block), a forest (low anxiety), a generic city (middling anxiety), and a house at night (high anxiety). Screenshots of the environments can be found in Figure 5.1. Initial inspiration for the environments came from preliminary results from the *Project Soothe* project (MacLennan et al., 2023). This was followed by a series of (currently unpublished) studies exploring emotional reactions to visual imagery in both 2D and immersive 3D imagery. The key insights from these studies were that natural environments with water were especially soothing, while visually busy urban environments were not. Meanwhile, the principles of horror media (Martin, 2019), such as uncertainty and uncanniness, were used in the house environment to encourage non-distressing levels of anxiety.

Participants were encouraged to explore and immerse themselves in these virtual environments for 5 minutes. After those 5 minutes, participants completed a block of the auditory search and detection tasks. Following the last trial of the block, participants took off the virtual reality headset and completed the Short State Anxiety Inventory. In each block, participants completed a trial for every combination of the target stimulus, critical stimulus presence, and number of non-target sounds 3 times. This resulted in each participant completing 144 trials in experimental blocks and 192 trials in total, when including the training block. The experiment took approximately an hour to complete.

Figure 5.1

Illustrative screenshots of the virtual environments explored by participants for the purposes of influencing their state anxiety. Going clockwise from the top left – 1) House at night, 2) generic city, 3) forest, and 4) low-polygon village.

5.3.6 Analysis

Analyses for this paper were conducted using the R statistical language (R Core Team, 2013) and the *lme4* package (Bates et al., 2015) was used for linear mixed effects models. Analysis scripts are available in appendix 8.6. Trial-level pupil dilation data were removed if the sensor reported under 100% confidence in its estimate and heart rate data were removed if the heart rate was under 40. Trials were removed from the analyses if the response time was under 150ms or 2 standard deviations above the mean reaction time. Finally, four participants were excluded due to correctly identifying the target stimulus in under 60% of trials. A single pupil dilation value was calculated for each trial as a mean average of the two eyes. Reaction time data were transformed using Tukey's ladder of powers to be approximately normal and all numeric variables were then mean-centred and scaled to have a standard deviation of 1.

The main analyses used linear mixed effects models. The random effects were selected using the principle of maximal estimation, while maintaining a non-singular fit. To do this, the maximum theoretically plausible random effects were included and then sequentially removed, as recommended by Barr et al. (2013). This process is documented in appendix 8.6. The number of stimuli presented to the participants was treated as an ordinal variable across the different models. Model comparisons were therefore used to judge the significance of the number of presented stimuli and their interactions.

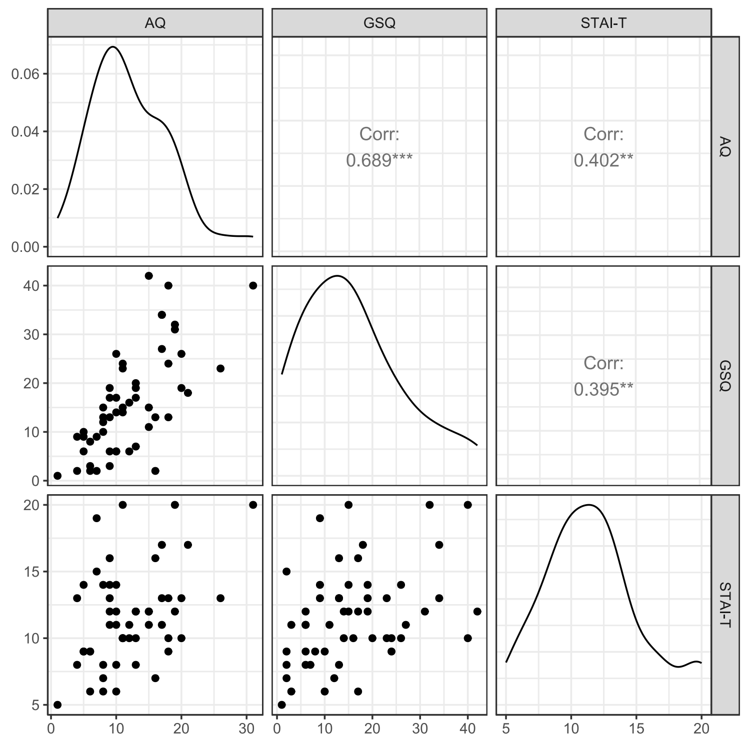
5.4 Results

5.4.1 Participant Trait Characteristics

As expected, significant correlations were identified between each of the Autism Spectrum Quotient, the Glasgow Sensory Questionnaire, and the State Trait Anxiety Inventory. Visualisations of the distributions and correlations between each of these trait measures can be seen in Figure 5.2. When corrected for multiple comparisons using the Benjamini-Hochberg method (Benjamini & Hochberg, 1995), all correlations remained significant. This includes the correlation between the Autism Spectrum Quotient Short and both the Glasgow Sensory Questionnaire Short (r (51) = .69, $p < .001$) and the Trait Anxiety Inventory Short (r (51) = .40, $p = .003$). The correlation between the Glasgow Sensory Questionnaire and Trait Anxiety Inventory Short was also significant (r (51) = .40, $p = .003$).

Figure 5.2

Scatterplots, density plots, and Pearson correlation coefficients of and between participant total scores on the Autism Spectrum Quotient Short (AQ), Glasgow Sensory Questionnaire Short (GSQ), and Trait Anxiety Inventory Short Scores (STAI-T).



Note. * = p < .05, ** = p < .01, *** = p < .001.

5.4.2 Virtual Environment Effectiveness

For this experiment, it was important that participants were experiencing different levels of anxiety throughout. As this was manipulated using the different virtual environments, it was deemed sensible to compare the potential anxiety measures across the environments to ensure that they were working as intended. Repeated-measures ANOVAs were conducted on the mean values of heart rate, heart rate variability, pupil dilation, and State Anxiety Inventory for each participant in each of the scenes. Details of these ANOVAs can be found in Table 5.2 and visual comparisons in Figure 5.3.

Only subjective state anxiety, measured using the State Anxiety Inventory, was found to vary significantly across the virtual environments in these data. The night-time house showed significantly higher reports of state anxiety (M = 0.60, SD = 1.14) than both the forest (M = -0.45, SD = 0.67) and city (M = -0.13, SD = 0.86) virtual environments. Based on these results, it was felt that the State Anxiety Inventory would be the best measure of state anxiety for the following analyses.

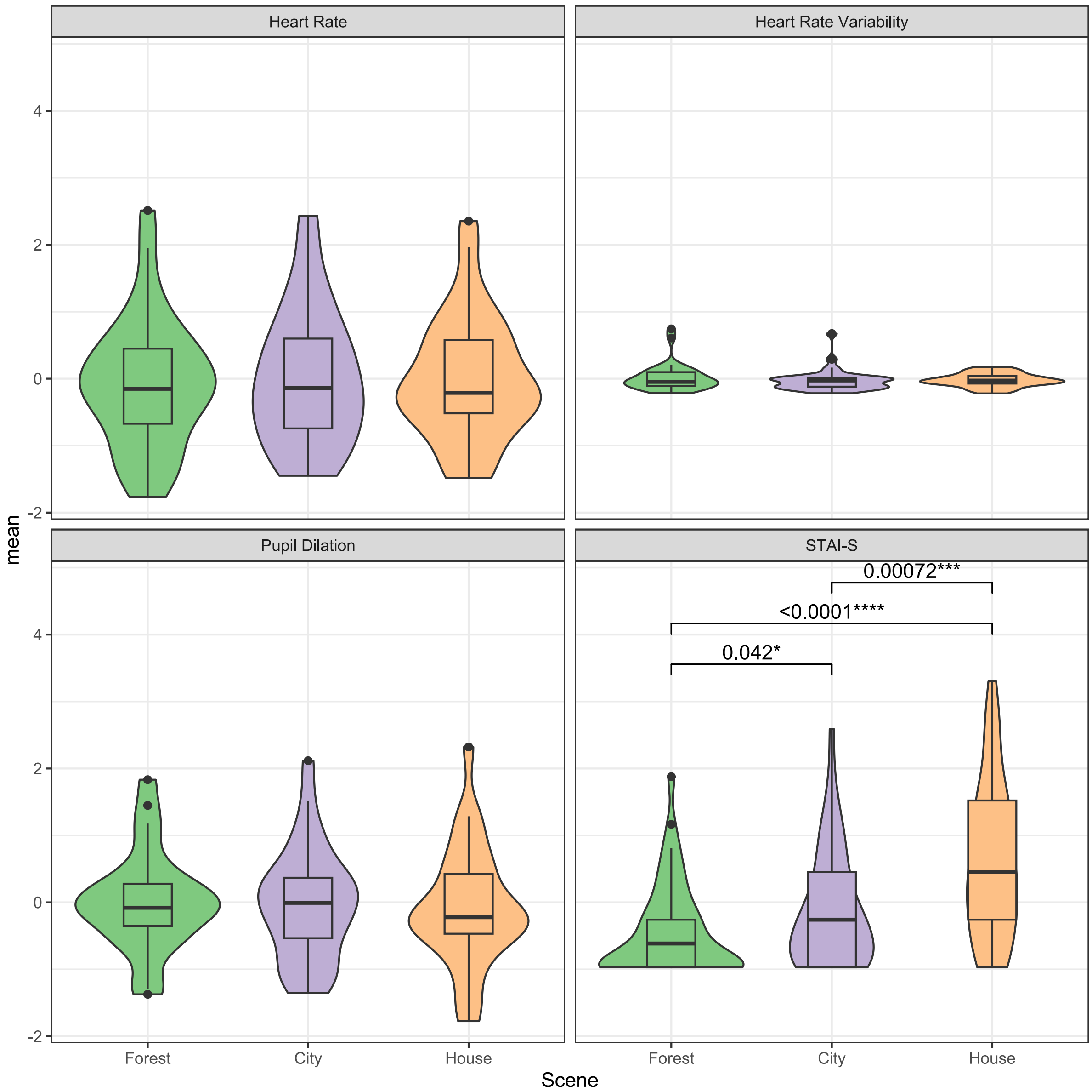
Table 5.2

Results From Repeated-Measures ANOVAs Comparing Measures of Anxiety Across Virtual Environments

Measure of Anxiety	Degrees of Freedom	F	p
Heart Rate	2, 58	0.74	0.48
Heart Rate Variability	2, 60	0.38	0.38
Pupil Dilation	2, 54	0.34	0.71
State Anxiety Inventory	2, 94	29.80	<0.001

Figure 5.3

Violin plots and boxplots across virtual environment scenes for distributions of participant heart rate, heart rate variability, pupil dilation, and score on the State Anxiety Inventory Short Scores (STAI-S). Each black dot indicates an outlier. Bold lines show median scores and boxes show interquartile ranges. Box whiskers represent the largest of the total range of the data or 1.5 times the interquartile range. Also shown are Bonferroni corrected p-values of significant Wilcoxon tests in post-hoc analyses.



5.4.3 Primary Search Task

Reaction time

The analysis of reaction times to complete the primary search task was conducted using a linear mixed effects model. Trials were excluded if the participant did not correctly identify the target stimuli. The number of presented sounds, Autism Spectrum Quotient score and their interaction were included as fixed effects to approximate the analysis from Remington & Fairnie (2017). State Anxiety Inventory and resulting interactions were also included as fixed effects. Participant and trial intercepts were included as random effects as the maximal non-singular solution. The simplification method is included in the analysis script. Replicating the results of Remington & Fairnie (2017) and conforming to prediction 4, only the stimuli set size significantly predicted reaction time for the primary task. Reaction times across set sizes can be found in Table 5.3. Estimated fixed and random effects are in Tables 5.4, 5.5, and 5.6. The marginal R^2 for this model was 0.03 and the conditional R^2 was 0.23.

Table 5.3

Mean Reaction Times (ms) and Mean Percentage Errors on the Auditory Search Task Across the Number of Presented Sounds

Set Size 1		Set Size 2		Set Size 4		Set Size 6	
Mean RT	Error%	Mean RT	Error%	Mean RT	Error%	Mean RT	Error%
1246	9.93	1396	15.85	1489	22.26	1496	29.72
(247)	(9.30)	(288)	(9.98)	(331)	(13.22)	(335)	(14.91)

Note. Standard deviations are presented in brackets.

Table 5.4

Fixed Effects from Linear Mixed Effects Model of Reaction Time when Completing the Primary Auditory Search Task

	Estimate/Beta	SE	95% CI	t	p
Intercept	-0.04	0.06	-0.17 – 0.08	-0.70	.485
Set Size – Linear	0.29	0.04	0.21 – 0.36	7.60	<.001*
Set Size – Quadratic	-0.10	0.04	-0.18 – -0.03	-2.74	.009*
Set Size – Cubic	-0.03	0.04	-0.10 – 0.05	-0.67	.508
AQ	0.01	0.06	-0.12 – 0.13	0.12	.906
STAIS	0.02	0.03	-0.03 – 0.08	1.09	.426
AQ x Set Size – Linear	-0.03	0.02	-0.08 – 0.01	-0.06	.175
AQ x Set Size – Quadratic	-0.00	0.02	-0.05 – 0.05	-0.10	.917
AQ x Set Size – Cubic	-0.01	0.03	-0.05 – 0.04	-0.21	.830
STAIS x Set Size – Linear	-0.02	0.03	-0.07 – 0.03	-0.63	.672
STAIS x Set Size – Quadratic	0.00	0.02	-0.05 – 0.05	0.02	.383
STAIS x Set Size – Cubic	-0.00	0.02	-0.06 – 0.04	-0.54	.597
AQ:STAIS	0.04	0.03	-0.01 – 0.10	1.47	.152

Table 5.5

Significance of Fixed Effects from Linear Mixed Effects Model of Reaction Time as Calculated Using Model Comparison

	Chi-square	df	P
Set Size	43.74	3	<.001*
Set Size x AQ	1.88	3	.597
Set Size x STAIS	0.68	3	.684

Table 5.6

Random Effects from Linear Mixed Effects Model of Reaction Time when Completing the Primary Auditory Search Task

	Variance	SD	Correlation
Trial (Intercept)	0.01	0.10	
Participant (Intercept)	0.17	0.41	
STAIS (Slope)	0.01	0.14	-0.07

Note. P-values for fixed effects were calculated using Satterthwaite approximations. Confidence Intervals were calculated using the Wald method. The equation for this model was: Reaction time ~ set size + AQ + STAIS+ set size:AQ + set size:STAIS + (1 + STAIS | participant) + (1 | trial).

Accuracy

A similar analysis was conducted on the accuracy of participants identifying the correct target stimulus. This involved a generalised linear mixed effects model with a binomial link function. The number of presented sounds, Autism Spectrum Quotient scores, State Anxiety Inventory scores and all interactions were included as fixed effects. State Anxiety Inventory scores, as well as participant and trial intercepts, were included as random effects. Again, like Remington & Fairnie (2017) and confirming prediction 4, this model identified only the size of the stimuli array to be statistically significant. Error rates for the primary search task can be seen in Table 5.7, fixed effects in Tables 5.8 and 5.9, and random effects in Table 5.10. The marginal R^2 for this model was 0.09 and the conditional R^2 was 0.28.

Table 5.7

Error Rates on the Primary Search Task

	Set Size 1	Set Size 2	Set Size 4	Set Size 6
Error%	27.63 (11.86)	34.23 (9.62)	46.48 (9.70)	51.09 (6.66)

Table 5.8

Fixed Effects from Logistic Mixed Effects Model of Accuracy when Completing the Primary Auditory Search Task

	Estimate/Beta	SE	95% CI	t	p
Intercept	1.69	0.14	1.42 – 1.96	12.24	<.001*
Set Size – Linear	-1.24	0.17	-1.57 – -0.91	-7.32	<.001*
Set Size – Quadratic	0.10	0.17	-0.22 – 0.43	0.62	.535
Set Size – Cubic	0.04	0.16	-0.28 – 0.36	0.25	.806
AQ	-0.15	0.11	-0.37 – 0.07	-1.31	.190
STAIS	0.01	0.06	-0.11 – 0.12	0.08	.935
AQ x Set Size – Linear	-0.07	0.07	-0.20 – 0.07	-0.99	.322
AQ x Set Size – Quadratic	0.12	0.07	-0.00 – 0.25	1.89	.059
AQ x Set Size – Cubic	0.08	0.06	-0.04 – 0.20	1.31	.192
STAIS x Set Size – Linear	0.14	0.08	-0.00 – 0.29	1.86	.063
STAIS x Set Size – Quadratic	-0.08	0.07	-0.22 – 0.07	-1.06	.291
STAIS x Set Size – Cubic	-0.11	0.07	-0.25 – 0.03	-1.52	.128
AQ:STAIS	0.06	0.05	-0.04 – 0.16	1.10	.271

Table 5.9

Significance of Fixed Effects of Accuracy when Completing the Primary Auditory Search Task as Calculated Using Model Comparison

	Chi-square	df	P
Set Size	36.30	3	<.001*
Set Size x AQ	6.71	3	.082
Set Size x STAIS	6.63	3	.085

Table 5.10

Random Effects from Logistic Mixed Effects Model of Accuracy when Completing the Primary Auditory Search Task

	Variance	SD	Correlation
Trial (Intercept)	0.01	0.10	
Participant (Intercept)	0.17	0.41	
STAIS (Slope)	0.01	0.12	-0.07

Note. P-values for fixed effects were calculated using Satterthwaite approximations. Confidence Intervals were calculated using the Wald method. The equation for this model was: Correct answer chosen ~ set size + AQ + STAIS + set size : AQ + set size : STAIS + (1 + STAIS | participant) + (1 | trial).

5.4.4 Secondary Detection Task

Trials were excluded if the participant's response to the primary task was incorrect. Participants' accuracy in detecting the critical stimulus was again used as the outcome variable in a generalised linear mixed effects model using a binomial link function with the same fixed and random effects as for the model assessing accuracy in the primary task. In contrast to Remington & Fairnie (2017) and predictions 1, 2, and 3, the model found no significant effects of set size, autistic traits, anxiety, or overall interactions, though it should be noted that the individual predictors representing the linear effect of set size and its interaction with the autism spectrum quotient score were significant. Participant error rates are displayed in Table 5.11 and model characteristics in Tables 5.12, 5.13, and 5.14. Using the delta method, the marginal R^2 was 0.05 and the conditional R^2 was 0.35.

Table 5.11

Error Rates on the Secondary Detection Task

	Set Size 1	Set Size 2	Set Size 4	Set Size 6
Error%	27.63 (11.86)	34.23 (9.62)	46.48 (9.70)	51.09 (6.66)

Table 5.12

Fixed Effects from Logistic Mixed Effects Model of Accuracy when Completing the Secondary Auditory Detection Task

	Estimate/Beta	SE	95% CI	t	p
Intercept	0.54	0.18	0.19 – 0.89	3.01	.003*
Set Size – Linear	-0.96	0.35	-1.65 – -0.27	-2.72	.006*
Set Size – Quadratic	0.16	0.35	-0.53 – 0.85	0.46	.643
Set Size – Cubic	-0.00	0.35	-0.69 – 0.68	-0.00	.997
AQ	0.03	0.05	-0.07 – 0.13	0.57	.566
STAIS	0.03	0.05	-0.06 – 0.11	0.57	.566
AQ x Set Size – Linear	0.18	0.07	0.03 – 0.32	2.41	.016*
AQ x Set Size – Quadratic	-0.05	0.07	-0.18 – 0.09	-0.68	.498
AQ x Set Size – Cubic	-0.01	0.07	-0.13 – 0.12	-0.09	.927
STAIS x Set Size – Linear	-0.10	0.08	-0.26 – 0.05	-1.35	.177
STAIS x Set Size – Quadratic	-0.04	0.07	-0.19 – 0.10	-0.61	.544
STAIS x Set Size – Cubic	0.08	0.07	-0.05 – 0.22	1.21	.228
AQ:STAIS	0.01	0.04	-0.07 – 0.08	0.18	.860

Table 5.13

Significance of Fixed Effects of Accuracy when Completing the Secondary Auditory Detection Task as Calculated using Model Comparison

	Chi-square	df	P
Set Size	7.14	3	.068
Set Size x AQ	6.82	3	.078
Set Size x STAIS	3.96	3	.267

Table 5.14

Random Effects from Logistic Mixed Effects Model of Accuracy when Completing the Secondary Auditory Detection Task

	Variance	SD
Trial (Intercept)	1.42	1.19
Participant (Intercept)	0.06	0.25

Note. P-values for fixed effects were calculated using Satterthwaite approximations. Confidence Intervals were calculated using the Wald method. The equation for this model was: Correct answer chosen ~ set size + AQ + STAIS + set size : AQ + set size : STAIS + (1 + STAIS | participant) + (1 | trial).

In summary, these results found that, contrary to predictions, neither autistic traits nor state anxiety, or any interaction between the two, significantly predicted accuracy on the secondary detection task. These predictors were also non-significant in models assessing accuracy and reaction times on the primary search task. Participant scores on the Glasgow Sensory Questionnaire Short, Autism Spectrum Quotient Short, and State Anxiety Inventory Short were all significantly correlated.

5.5 Discussion

This study tested the perceptual capacity of participants across three different virtual environments to modulate their state anxiety. This was achieved using a dual-task paradigm under different levels of perceptual load, where participants were asked to perform a primary auditory search task and a secondary auditory detection task. Although state anxiety varied significantly between virtual environments, analysing participant reaction times or accuracy on the primary search or detection tasks did not reveal any significant effects of anxiety or autistic traits. Analysis of participant questionnaire responses showed that autistic traits, sensory reactivity, and trait anxiety were all significantly correlated with each other.

The lack of significant predictors relating to anxiety or autistic traits for reaction times and accuracy on the primary auditory search task was expected and is consistent with previous work with autistic participants (Remington et al., 2009; Remington & Fairnie, 2017). This finding is also consistent with experiments using a similar paradigm with measures of trait anxiety (Berggren et al., 2015; Sadeh & Bredemeier, 2011). It is notable that experiments using only the search task, without the secondary detection task, more regularly find that higher reactions are associated with higher anxiety (Shi et al., 2019). It is not obvious whether these differences represent a different attentional process when adding the second task, or if the additional analytical complexity leads to the dual-paradigm studies being underpowered.

In contrast to the previous body of research, no interactions were identified between perceptual load and measures of autistic traits or state anxiety in the secondary auditory detection task. This was surprising, as both autistic people (Remington et al., 2009; Remington & Fairnie, 2017) and people with higher anxiety (Berggren et al., 2015; Sadeh & Bredemeier, 2011) are typically identified as having a higher perceptual capacity than non-autistic people. This was also surprising given the results from the correlational analyses which conformed to previous research (Horder et al., 2014) and found significant correlations between each combination of trait anxiety, autistic traits, and sensory reactivity.

Closer examination of the model used to analyse participants' accuracy on the secondary task offers some insight into the cause of these results. Within the model, set size (representing perceptual load) was not significant. Looking at the error rates, participants were also reaching chance-level accuracy at 4 played stimuli. Together, these imply that the stimuli used in this study were more difficult to detect than the stimuli by Remington & Fairnie (2017). This could have been because of differences in the program used to play the stimuli, the physical audio hardware, or the choice of sound files used. In this context, it was unexpected that there was an interaction between autistic traits and the linear estimate for set size. It is prudent to not overstate the importance of this predictor in light of the insignificance of the overall interaction and the number of statistical inferences made within the model. Yet, if the effect of autistic traits on perceptual capacity is non-zero but relatively small, a better difficulty differential may allow for it to be observed.

Another possibility is that perceptual capacity is not the best model for exploring the overlap between sensory reactivity and anxiety. Load theory has been the subject of several criticisms, most notable of which is that the definitions of perceptual load and capacity are nebulous, leading to imprecise conceptualisations and operationalisations (G. Murphy et al., 2016). For example, the expected results from load theory are used to determine that perceptual load has been successfully manipulated, rather than an independent indicator, leading to potential circular reasoning (Roper et al., 2013). There is also uncertainty as to whether the principles of load theory derived from visual attention can apply to auditory tasks (S. Murphy et al., 2017). As a plethora of theories exist to explain both sensory reactivity and anxiety, including attentional theories, it would be worth exploring some of these alternatives.

5.5.1 Limitations and Future Directions

It was reported that data collection for this study took place over two blocks. It was initially intended for this chapter to be two separate studies, the first of which would be a pilot study testing the procedure and virtual environments. The second study was planned to be a comparison between autistic and non-autistic people. Unfortunately, there were several logistical difficulties, which led to the two studies being combined for this chapter. Among these was unexpected masonry work in the vicinity of the research lab during experimental sessions, which likely only added to the difficulty of the task. It was also hoped that heart rate and pupil-dilation data could offer a biometric measure of arousal and/or anxiety throughout the tasks. However, over the course of data collection, it became apparent that participants' physical and emotional engagement with the virtual environments had a much larger effect on these measures. Future iterations of this paradigm should encourage participants to limit their movement, such as by maintaining a sitting position. As Virtual Reality continues to disseminate through the population, it is also likely that the novelty effects on arousal will reduce over time.

A core limitation of this study is that it relied on autistic traits to make inferences about autistic people more widely. While this has been done consistently through the field (Ruzich, Allison, Smith, et al., 2015), including in experimental studies of sensory processing (Yaguchi & Hidaka, 2020), this choice to diverge from other similar studies like Remington & Fairnie (2017) which used diagnostic groupings may have influenced the findings. For example, it is possible that increased sensory capacity is only expressed when a specific threshold of autistic traits is crossed. Equally, it is possible that by including more participants in the middle of the distribution of autistic traits, rather than the higher tails, the power of this study to identify any relationships may have been reduced. As such, it would be beneficial for future iterations of the study to compare autistic and non-autistic participants.

5.5.2 Conclusion

This study was the first to attempt to measure the effects of state anxiety on perceptual capacity or autistic sensory processing using an experimental paradigm. By moving away from a sole reliance on questionnaire-based studies, the aim was to capture a short-term phenomenon. The results ultimately showed no effects of autistic traits or state anxiety on the detection of the critical stimulus, implying no effect on perceptual capacity (Berggren et al., 2015; Remington et al., 2009; Remington & Fairnie, 2017). However, several difficulties with the study were identified, meaning that the null results should not necessarily be identified as evidence against the primary anxiety model. Analysis of the statistical models suggests the tasks completed by the participants may have been too difficult, masking any effects of autistic traits or state anxiety. Equally, experimental investigation of alternate models of sensory reactivity may identify stronger effects. The strengths of the newly developed experimental paradigm are such that they should continue to be applied to inquiries in the anxiety and sensory processing research field.

6. General Discussion

6.1 Summary of Findings

The aim of this thesis was to explore the causality of the relationship between anxiety and sensory reactivity in autistic people. It was hoped that a bidirectional relationship could be described and demonstrated. Before this could be directly addressed, several methodological and theoretical questions also needed to be answered.

The first study (Chapter 2) was a qualitative survey, co-produced with autistic people who were meaningfully engaged at every stage of the research process, asking about autistic experiences of sensory overload. Besides offering useful insight into the phenomenon itself, it was intended that participant descriptions of their extreme sensory experiences be a useful prism through which the potential bidirectional relationship between anxiety and sensory reactivity could be observed. The results highlighted slight disagreements between participants about what defined sensory overload, i.e. whether the physical reaction or the disruption of functioning was the key signifier. However, the key insight was that processing all the incoming sensory information during overload expended a lot of energy. Based on participant responses, it appeared as though that energy was being used to increase the capacity of processes throughout the cognitive pipeline. If the perceptual and attentional capacities could no longer be expanded, whether because of hitting hard limits or being fatigued, they would be overwhelmed and lead to the sensations associated with sensory overload. Anxiety was present throughout participant accounts as both a consequence and a contributory factor of sensory overload.

As an experiential basis for a bidirectional relationship between anxiety and sensory reactivity had been established in Chapter 2, the project pivoted toward a quantitative approach. During the planning process, it became apparent that the original Glasgow Sensory Questionnaire (A. E. Robertson & Simmons, 2013) took a long time to complete, increasing both the cost of participants' time and attrition rates. Chapter 3 therefore describes the construction of the Glasgow Sensory Questionnaire Short. This was achieved in two stages. In the first stage, datasets containing item-level scores on the original Glasgow Sensory Questionnaire were identified and then shared with the researcher. These data were then used to test a series of confirmatory factor analysis models. The best fitting model identified a second-order structure where each subscale formed a latent variable, each of which then loaded onto a general 'sensory reactivity' factor. The item in each subscale with the highest loading was then selected to include in the short form questionnaire. A second sample was then collected to validate the performance of the Glasgow Sensory Questionnaire Short in a research setting, where it was found to have good internal consistency and concurrent validity with the Autism Spectrum Quotient Short. As well as producing a useful research tool, this study confirmed that sensory reactivity, as defined within the Glasgow Sensory Questionnaire, captures a singular concept, despite significant variation in its expression.

Over the course of this PhD, the neurodiversity movement continued to grow in relevancy. Given the concurrent prominence of attention-based explanations of sensory reactivity and anxiety in autistic people, it was felt to be important to explore potential overlaps between sensory reactivity, autism, ADHD, and other neurodivergent conditions. If sensory reactivity were to be a neurodivergent experience, as much as an autistic one, explanations of sensory reactivity would have to become more general. The study described in Chapter 4 therefore asked a general population sample and a neurodivergent sample to complete screening questionnaires for ADHD, autism, and dyslexia. The analysis used latent variables and structural equation modelling to identify that both ADHD and autistic traits explained variance in sensory reactivity beyond their relationship with each other. Any relationship between dyslexia and autism was also found to be entirely attributed to their shared relationship with ADHD. Based on this result and well-known diagnostic overlaps between autism and ADHD, it was concluded that research on sensory reactivity should consider traits from both conditions. This result was consistent with attentional processes influencing sensory reactivity.

The final study described in Chapter 5 was an experiment designed to elicit changes in sensory reactivity by modifying and measuring state anxiety. This was achieved using a dual-task paradigm previously used by Remington & Fairnie (2017), intended to measure each participant's sensory capacity. Anxiety levels of participants were manipulated with a succession of Virtual Reality environments, within which participants completed the experimental task and explored using a head-mounted display. These Virtual Reality environments were solely designed and created by the researcher for this thesis, using inspirations from ongoing research about soothing imagery and horror media, as well as unpublished studies applying these principles to Virtual Reality. The results from this experiment were inconclusive, finding no significant interactions between perceptual load and autistic traits or state anxiety. Given the number of novel components to this study, it is unclear which of these led to divergent outcome from previous efforts. However, the questionnaire elements confirmed the long-running associations between sensory reactivity, autistic traits, and trait anxiety.

6.2 Theoretical Perspectives

The theoretical anchor for this thesis is the three models put forward by Green & Ben-Sasson (2010) as potential explanations for the relationship between sensory reactivity and anxiety in autistic people. The first was termed the 'Primary Anxiety' model, which suggested that higher levels of anxiety cause higher sensory reactivity, potentially because factors such as attentional and expectancy biases lead autistic people to be more attentive and, therefore, reactive to adverse sensory stimuli. In the second model, called the 'Primary Sensory Over Responsivity' model, higher sensory reactivity would trigger higher anxiety. The proposed mechanism for this model was that autistic people would be more likely to find everyday sensory stimuli unpleasant or painful. They would then be more likely to associate negative sensations with uncertain sensory stimuli, leading to generalisable anxiety. In their final model, Green & Ben-Sasson (2010) also propose that anxiety and sensory reactivity could arise because of an underlying third factor that both are related to. Examples they gave included potential diagnostic overlap between autism and anxiety, as well as the functioning of the amygdala.

Following the publication of Green et al. (2012), a longitudinal study in toddlers which found that sensory processing differences arose first and were then followed by the development of anxiety symptoms, most research attention has been paid to the 'Primary Sensory Over Responsivity' model. This is not without merit – research has consistently found reported sensory processing differences to be consistent over time (Dwyer et al., 2020; Perez Repetto et al., 2017). Direct comparisons between the models using questionnaire data have also found the Primary Sensory Over Responsivity model to have a better fit (Amos et al., 2019) and experiments have reported that sensory tasks can induce physiological anxiety (Jung et al., 2021; S. J. Lane et al., 2012). Extensions of this model, such as models incorporating intolerance of uncertainty, have established their own evidence bases (Hwang et al., 2020; Normansell-Mossa et al., 2021; Wigham et al., 2015). Based on this research, we can be confident that sensory processing differences lead to increases in anxiety.

This thesis was embarked upon with the premise that while there was significant evidence for the Primary Sensory Over Responsivity model, there was not necessarily evidence against the Primary Anxiety model. The mechanisms used to explain the Primary Sensory Over Responsivity model describe the development of trait anxiety, which then influences the expression of state anxiety. This suits questionnaire studies which use measures of trait anxiety, such as Green et al. (2012) or Amos et al. (2019). Meanwhile, the few experimental studies in this area have only manipulated the sensory experiences of their participants (Jung et al., 2021; S. J. Lane et al., 2012). Yet, the mechanisms proposed by Green & Ben-Sasson (2010) for the Primary Anxiety model primarily concerned the effects of state anxiety on immediate sensory experiences, which would not be captured by these methods.

In qualitative studies asking autistic people about their sensory differences, participants have described how the intensity of their negative differences can be affected by their mood. For example, MacLennan et al. (2021) developed a 'Moderated by Mood' sub-theme where some of their respondents reported they could tolerate adverse stimuli when they were well-rested and/or not stressed, but would react negatively if the opposite were the case. Similarly, participants in the focus group conducted by Robertson & Simmons (2015) reported both hyper- and hypo-reactivity to sensory stimuli when in anxious states in the 'Mental States and Emotions' theme. These reports imply that anxiety does influence at least one of the sensory processing levels.

The findings in Chapter 2 relating to anxiety were very similar to those identified by Robertson & Simmons (2015) and MacLennan et al. (2021). First, the Primary Sensory Over Responsivity model was validated by the prominence of the acute stress response to the experience of sensory overload, both for those who viewed the response as the fundamental characteristic of sensory overload and those who viewed it as a secondary reaction. Notably, however, participants also reported a couple of different ways anxiety affected their sensory processing. The first of these were described in the *'Interoceptive and Exteroceptive Sensation'* and *'Role of '* sub-themes, where anxiety appeared to be one of the sensory inputs contributing to sensory overload. This makes sense, as the acute stress response has been well understood to affect numerous internal bodily and interoceptive systems, such as heart rate, muscle function, and digestion (Benarroch, 2014). Many of these have been identified as interoceptive areas where autistic people can struggle (J. Murphy, Catmur, et al., 2018; A. E. Robertson & Simmons, 2015). Therefore, if a person is anxious, they will process additional input from their bodily systems, which will affect their processing of other stimuli and make them more likely to slip into overload.

The second potential mechanism for anxiety to affect sensory processing, as implied by the *'Role of '* and *'Uncertainty'* subthemes of Chapter 2, was more cognitive in nature. According to the *'Overload of Higher-Level Attentive Capacity'* theme, cognitive demands like navigating social situations or decision making could contribute to sensory overload and, presumably, impact sensory reactivity/responsivity. The processing efficiency theory (Eysenck & Calvo, 1992) proposes that anxious thoughts consume cognitive resource. If this is the case, these additional thoughts directly contribute to sensory overload and reactivity by exceeding processing capacities. If, alternatively, the attentional control theory (Eysenck et al., 2007) is a more accurate representation of reality, higher levels of anxiety would mean that autistic people would be more likely to direct those cognitive resources toward potentially averse sensory stimuli. This would lead to increased sensory reactivity and reduce the attention that could be paid to processes necessary for context-dependent functioning.

These findings support a model integrating both the Primary Sensory Over Responsivity and Primary Anxiety explanations of the link between sensory processing and anxiety. The Primary Sensory Over Responsivity explanation describes the long-term experience of the autistic person such that neurodevelopmental differences lead to a more sensorily adverse environment from birth, leading to negative associations with everyday experiences. This widespread negative conditioning leads to higher trait anxiety, which in turn is expressed in the person as more intense and frequent state anxiety. Conversely, effects of higher levels of state anxiety on attentional processes, such as attentional biases toward adverse sensory stimuli and efforts to expand sensory processing capacities, lead to the person experiencing greater sensory reactivity in the short-term. If the person were to be often in a highly anxious state, this would lead to a higher sensory reactivity over the medium to long term, leading to higher anxiety. According to this model, sensory reactivity and anxiety would form a cyclical relationship with each other.

Using the framing here, this would appear to be a vicious cycle, but with appropriate intervention, it could also become virtuous.

One potential challenge is that single-factor psychometric tools may be an imperfect measure of sensory reactivity, especially in the context of its relationship with anxiety. For example, Ausderau et al. (2014) identified a complex factor structure of the Sensory Experiences Questionnaire, which included latent variables for each of the modalities, social context, and question type. MacLennan et al. (2020), meanwhile, found that subscales on the Sensory Processing Scale Inventory (Schoen et al., 2017) representing hyper-reactivity, hypo-reactivity, and sensory seeking behaviours had unique relationships with different subscales of the Spence Children's Anxiety Scale (Edwards et al., 2010; Nauta et al., 2004). While primarily intended to develop a shorter Glasgow Sensory Questionnaire, the Confirmatory Factor Analysis used in Chapter 3 found that treating sensory reactivity as a single factor was reasonable, albeit understanding that each of the subscales also accounted for some of their own variance. This finding was consistent with other research using similar methods and questionnaires (Weiland et al., 2020; Z. J. Williams et al., 2023). It was therefore felt reasonable to continue to use total scores for both the Glasgow Sensory Questionnaire and Glasgow Sensory Questionnaire Short, though it may not be a perfect representation of reality.

While the structure of the Glasgow Sensory Questionnaire and sensory reactivity was more settled, over time, it became apparent that the relationship between autism and sensory reactivity may also have been more complex than initially believed. It has long been understood that both autism and ADHD have overlapping diagnostic characteristics and high rates of co-occurrence (APA, 2022; Rong et al., 2021). While both neurodivergences were associated with sensory elements (W. Dunn & Bennett, 2002; Kientz & Dunn, 1997), it is only recently that more attention has been paid to the extent to which sensory reactivity differences are similar between the conditions (Panagiotidi et al., 2018). Further, the finding from Dellapiazza et al. (2021) that autistic children with ADHD scored higher on subscales of sensory reactivity than children with only a single neurodivergent condition suggested that neither autistic nor ADHD traits could alone account for sensory reactivity differences.

Similarly to sensory reactivity, autistic people and people with ADHD are both more likely to be anxious (Hollocks et al., 2019; Jarrett & Ollendick, 2008). Autistic children with ADHD also seem to have higher anxiety than if they have a diagnosis of only one or the other (Avni et al., 2018). This again suggests that ADHD and autism have interacting relationships with anxiety, which could feasibly apply when examining sensory reactivity at the same time. This was confirmed by Varbanov et al. (2023) who used a graph network approach to identify that autistic and ADHD traits formed a community with each other that was then linked to a sensory reactivity community through anxious traits. As well as having implications for the Primary Anxiety model of sensory reactivity and the sensory-first account of autism (Falck-Ytter & Bussu, 2023), the finding inserted ADHD as an additional factor to be considered in explorations of the relationship between anxiety and sensory reactivity.

To contribute additional complexity, neurodiversity and neurodivergences are increasingly being considered as a whole (Dwyer, 2022). This includes Apperly et al. (2023) who measured traits of autism, ADHD, sensory reactivity, and several other neurodivergences simultaneously. With this data, Apperly et al. (2023) found that they could be best modelled using a single factor representing 'neurodiversity'. Faced with this emerging landscape, Chapter 4 aimed to replicate the findings of Apperly et al. (2023) and assess the extent to which sensory reactivity could be explained by autistic traits versus measures of other neurodivergences, including ADHD. Once complete, these findings could be extended to include anxiety. Ultimately, the combination of condition-specific and a single 'neurodiversity' factor proposed by Apperly et al. (2023) could not be tested, as the model was too complex to be identified. Instead, the best fitting models used each questionnaire as a latent variable, each of which could vary with each other.

Looking more closely at the estimated coefficients in Chapter 4, autistic and ADHD traits were both closely related to each other and to sensory reactivity. In contrast, dyslexic traits had little to no relationship with either sensory reactivity or autism but did significantly co-vary with ADHD traits. First, this would suggest that, while neurodivergences have high co-occurrences with each other, it would be too simplistic to consider only a 'neurodiversity' factor. That said, at least in these data, autism and ADHD appear to be the closely linked in both their direct covariance and relationships. This confirms previous research identifying that autism and ADHD not only overlap but also interact with each other on factors outside the diagnostic criteria (Dellapiazza et al., 2021; Rong et al., 2021). To extrapolate further, if ADHD and autism have individual and interacting relationships with sensory reactivity, this is also likely to apply to sensory reactivity's relationship with anxiety, as first described in Varbanov et al. (2023).

It remains possible that autism and ADHD's shared relationships with sensory reactivity can be entirely attributed to imprecise diagnostic criteria (Antshel & Russo, 2019), which will be explored further in future research. Assuming that this is not the case, shared attentional mechanisms (Sokolova et al., 2017) become increasingly interesting as an explanation for sensory reactivity and responsivity differences for both autism and ADHD. With this in mind, alongside the insights from autistic people in their descriptions of sensory overload in Chapter 2 and recent qualitative work (Irvine et al., 2024), the perceptual capacity model advanced by Remington et al. (2009) appeared as the most potentially fruitful of the models described in Section 1.2.2.

As an extension of the load theory of selective attention (Lavie et al., 2004), Remington et al. (2009) proposed that, irrespective of task demands, our perceptual capacity is always fully utilised. When completing a simple task that does not use the entire perceptual capacity, non-task relevant information will also be processed, potentially leading to distraction from the task at hand. Dual task paradigms have found that autistic participants can consistently detect secondary stimuli regardless of the number of distractors, while the performance of non-autistic people on this task reduces with increasing difficulty (Remington et al., 2009, 2012). These findings imply that autistic people have a greater capacity to process sensory information. Electrophysiological studies using people with higher autistic traits also seem to support this conclusion (Dunn et al., 2016; Lau-Zhu et al., 2019). There is also tentative evidence that this increased capacity applies to cognitive processes, as well as perceptual processing (Brinkert, 2021).

As described above, both load theory — and its progeny attentional control theory — have been applied to anxiety. Anxious people appear to have a lower processing efficiency but similar absolute effectiveness when completing experimental tasks, as well as general difficulties with attention switching (Shi et al., 2019). This has been found in participants with both high trait anxiety (Derakshan et al., 2009) and high state anxiety (Berggren et al., 2015). It follows that individuals with high anxiety not only possess greater perceptual capacity but also have the ability to enhance it based on current anxiety or other motivational factors. This story is like that described by participants in Chapter 2, where a person could continue functioning in the face of a high perceptual load by exerting energy. If they could not maintain that increased capacity, they would be overloaded. Given the high anxiety experienced by a high proportion of autistic people (van Steensel et al., 2011), this again raised the possibility that autism and anxiety could both contribute and interact with each other to increase perceptual capacity and, therefore, sensory reactivity. The experiment described in Chapter 5 was therefore developed to test whether these different effects could be observed experimentally.

Based on the previous literature using the dual-task paradigm (Berggren et al., 2015; Remington & Fairnie, 2017; Tillmann & Swettenham, 2017) and the conclusions from the preceding studies of this thesis, the results from Chapter 5 were surprising. No significant interactions between perceptual load and autistic traits or state anxiety were identified. Several methodological improvements were identified, which will be rectified in future work to determine whether this null result was a consequence of these flaws. Alongside these operational concerns, there is also the possibility that perceptual load is not a perfect model for understanding sensory reactivity, anxiety, or the relationship between the two. Concerns have previously been expressed that perceptual load and load theory more generally are not specific enough to enable predictions beyond the experimental tasks from which it was developed (G. Murphy et al., 2016; S. Murphy et al., 2017). Experiments using the dual-task have also identified anxious people as being both more and less likely to detect the secondary stimulus (Berggren et al., 2015; Sadeh & Bredemeier, 2011). These issues suggest that perceptual capacity may not be the most robust explanation for these phenomena.

The aim of Chapter 5 was to identify a mechanism that could affect and be affected by both sensory reactivity and anxiety. If replications of Chapter 5 are not fruitful, there are alternative explanations for the causal effect of anxiety on sensory reactivity alluded to by participants in Chapter 2 in their descriptions of sensory overload. For example, sensory sensitivity may be different in autistic people, independent of anxiety, because of divergences in neurodevelopment. Sensory reactivity may then result from well-established attentional biases associated with anxiety (Aue & Okon-Singer, 2015; Beck et al., 2005), where similar processes have been shown to increase affective sensory distress (Todd et al., 2016). Alternatively, as Bayesian models of autistic sensory reactivity and anxiety mature (Stark et al., 2021b), a more comprehensive understanding of the interactions between anxiety, autistic traits and behaviours, and perceptual priors may emerge. All these explanations have merit, including perceptual capacity, and deserve exploration in future work to validate the experiences and research demands of the autistic community.

6.3 Limitations and Future Directions

In the original project plan, this thesis was expected to have a stronger empirical focus, using Virtual Reality to manipulate participant state anxiety. This was in response to a literature base that was largely questionnaire based, which often used caregiver or clinician reports. However, as the project began in 2020, this plan was hugely disrupted by the COVID-19 pandemic. Not only was in-person experimentation legally restricted, but personal health concerns and supply chain interruptions meant that access to the specialised equipment was limited and delayed. Even once the practical limitations of the pandemic eased, several iterations of data collection were disturbed by implementation issues and equipment failures. Consequently, only a single experimental chapter was included in this thesis and the others were online questionnaires. As these practical challenges have now been overcome, replications and extensions of the procedure used in Chapter 5 would be fruitful to disentangle the relationships of anxiety and autism in the expression of perceptual capacity and sensory reactivity.

This thesis was also not conducted entirely sequentially, with the projects being staggered and overlapping. This was fruitful from a project management perspective; however, it meant that not all insights were implemented. For example, measures of ADHD traits were not included in Chapter 5, despite the findings of Chapter 4. Similarly, a measure of anxiety was not included in Chapter 4, despite the emergent findings of Varbanov et al. (2023) and Chapter 2. The apparent non-linear relationships between the different concepts identified throughout this thesis suggest that research considering each factor in isolation is missing potential explanatory power.

More fundamentally, because of the reliance on online self-administered questionnaires, this thesis did not broach the autistic population with greater support needs or co-occurring learning disabilities who would not have been able to participate. This continues a theme present throughout the wider neurodivergent research field (Jack & A. Pelphrey, 2017), leading to this sub-population being understudied and underserved (Cooper et al., 2022). This is especially relevant in the study of sensory reactivity and mental health, with initial research suggesting there is a particularly strong relationship between the two in people with few words (Rossow et al., 2021, 2023). While it is not as easy to work with people with fewer words, future research should allocate more attention to their needs.

Another concern is the nature of the population being studied throughout this thesis. As mentioned and shown in Chapter 4, the nature of autism is evolving. Traditionally, the diagnostic criteria for a diagnosis of Autism Spectrum Disorder (or its predecessors) has been relatively strict, requiring specific behaviours from early childhood which cannot be otherwise explained and are sufficiently disruptive to the person's wellbeing (Rosen et al., 2021). Over time and beginning in the 1990s, this smaller population has expanded to include more people (Russell et al., 2022) and the neurodiversity movement has led to a greater awareness of not only autism but how autistic traits can interact with other neurodivergences (Dwyer, 2022). In the spirit of inclusiveness and to address historical inequalities in access to diagnostic services (Overton et al., 2023), the autistic people included in the studies described here were only asked to self-identify as autistic. This group is likely to be very different, particularly regarding gender, then previous cohorts. Similarly, to capture the heterogeneity of autism (Abu-Akel et al., 2019), this thesis made significant use of the Autism Spectrum Quotient (Baron-Cohen et al., 2001) which has been critiqued for both its weakness as a diagnostic tool (Russell et al., 2015) and for being constructed with out-dated diagnostic criteria (Jia et al., 2019). In light of this shifting landscape, careful consideration should be given as to the theoretical basis for different effects. For example, it may be possible that the effects of anxiety on sensory processing are only notable in the smaller, clinical samples and unrelated to more dimensional sensory effects (A. E. Robertson & Simmons, 2013).

The studies of this thesis opened many avenues for future research. Particularly, Chapter 2 demonstrated the value of qualitative studies of different aspects of the sensory experience. Even when limited to sensory overload, methods which allow for further depth could be invaluable for confirming the specific insights presented and refining the process model of sensory overload, as visualised in Figure 2.1. Further, experimental studies like Chapter 5 could be deployed to test each of the hypothesised relationships. For example, Chapter 5 attempted to assess the validity of the causal link between emotional arousal/anxiety and higher-level processing. However, equally interesting and potentially fruitful avenues could be the fatigue effects of perceptual capacity tasks.

6.4 Implications

The key finding from the studies included in this thesis is that while the Primary Sensory Over Responsivity model proposed by Green & Ben-Sasson (2010) has a consistent evidence base over the long term, it is likely that the Primary Anxiety model is also appropriate in the short term. This may re-open the Primary Anxiety model as an avenue of research, which has been neglected since the publication of Green et al. (2012). The findings of Chapter 2 strongly point toward attentional processes like the biases toward aversive sensory stimuli (Bar-Haim et al., 2007) or increased perceptual capacity as key mechanisms.

Meanwhile, the results from Chapter 4 suggest that attentional mechanisms shared between autistic people and people with ADHD could be key for understanding sensory reactivity more generally. This finding is even more intriguing given the finding from Chapter 3 which found that sensory reactivity is best derived from a single underlying latent factor, which implies that even when considering multiple neurodivergences, sensory reactivity may form a single shared dimension.

Acknowledgement of a causal relationship from anxiety to sensory reactivity may be useful for both autistic people and practitioners working with autistic people. For example, the use of anxiety calming techniques could be vital for people who are immersed in sensorily adverse environments to reduce both their proximate anxiety and their reaction to the sensory environment, until they can leave or change that environment. Further, this provides an additional element which an autistic person can control, which itself can be helpful for people to navigate everyday situations. Meanwhile, from a more structural perspective, if anxiety can increase sensory reactivity, sensory accessibility efforts should consider high anxiety environments, such as school canteens and exam halls or hospitals.

6.5 Conclusion

This thesis has explored several aspects of sensory reactivity associated with autistic people, with an underlying thread exploring how it is likely to be affected by anxiety. This was achieved by investigating autistic experiences of sensory overload as the extreme of sensory processing difficulties (Chapter 2), the latent structures of questionnaires relating to sensory reactivity and neurodivergences (Chapters 3 and 4), and an experimental task looking at how state anxiety affected perceptual capacity (Chapter 5). These studies found that not only does increased state anxiety likely lead to increased sensory reactivity in the moment, but also that sensory reactivity as a dimensional concept has a relationship with ADHD beyond a shared co-occurrence with autism. Considering the results contained within this thesis, future work should aim to understand and disentangle the interweb of relationships between autistic and ADHD traits, anxiety, and sensory reactivity.

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8. Appendices

8.1 Finalised Glasgow Sensory Questionnaire Short Items

Table 8.1

Modality	Direction	Item	Question
Auditory	Hyper	31	Do you react very strongly when you hear an unexpected sound?
	Hypo	33	Do you really like listening to certain sounds (for example, the sound of paper rustling)?
Gustatory	Hyper	26	Do you use the tip of your tongue to taste your food before eating it?
	Hypo	28	Do you think you have a weak sense of taste? One example of this would be if most food tastes of ‘nothing’?
Olfaction	Hyper	24	Do you avoid going to restaurants because you can smell a certain odour?
	Hypo	17	Are you ever told by others that you wear too much perfume/aftershave?
Proprioception	Hyper	41	Do you like to wear something/hold something (for example, a hat or a pencil) so that you know where your body ‘ends’?
	Hypo	29	Do you find that you are unaware of your body’s signals (for example, don’t often feel hungry/tired/thirsty)?
Tactile	Hyper	15	Do you dislike having a haircut (for example, because little bits of hair go down your back)?
	Hypo	27	Does your body ever feel ‘numb’ - like you can’t feel anything against your skin?
Vestibular	Hyper	30	Do you ever feel dizzy/ill when playing fast-paced sports, for example basketball or football?
	Hypo	34	Do you like to run about – perhaps up and down in straight lines or round in circles?
Vision	Hyper	11	Do you find yourself fascinated by small particles (for example, little ‘bits’ of dust in the air)?
	Hypo	42	Do you flick your fingers in front of your eyes?

8.2 Auditory Search and Detection Task Stimuli Properties

Table 8.2

Sound	Frequency Range between -18dB points, Hz	Main Spectral Peaks, Hz	Periodicity
Car	108 – 646	230	Noise-like
Chicken	409 – 1830	451, 799, 1680	Somewhat periodic
Cockerel	1033 – 3467	1030, 2050, 2514, 3214	Moderate periodic
Cow	215 – 495	246, 495	Periodic
Crow	258 – 1895	265, 1237, 1843	Moderately periodic
Dog	538 – 1658	552	Somewhat periodic
Duck	388 – 2153	420, 846, 1265, 2131	Periodic
Lion	172 – 517	206, 497	Noise-like

8.3 Autistic Accounts of Sensory Overload and Implications for Sensory Reactivity Data

The questionnaire and lay person summary of the themes can be found at: https://osf.io/8qzdt/. The data are available at: https://reshare.ukdataservice.ac.uk/856923/.

8.4 Development and Validation of the Glasgow Sensory Questionnaire Short Data and Analysis Scripts

The data and analysis for this chapter can be found at: https://osf.io/duqvx/.

8.5 Modelling the Relationship between Neurodivergences and Sensory Reactivity Data and Analysis Scripts

The data and analysis for this chapter can be found at: https://osf.io/d6e4s/.

8.6 Measuring the Effect of State Anxiety on Sensory Capacity using Virtual Reality Data and Analysis Scripts

The data and analysis for this chapter can be found at: https://osf.io/6uy4e/.