Subjective sensory sensitivities as a transdiagnostic experience: characterisation, impact, and the development of the Cardiff Hypersensitivity Scale

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Thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

2023

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Thesis summary

Subjective sensory sensitivity refers to first person reports of experiencing sensory information as aversive, distracting, or overwhelming. Precursors to the experience occur across sensory modalities, ranging from bright lights and loud noises to rough fabrics and strong tastes. Study of subjective sensitivities commonly focuses on specific groups; for example, sensitivities are well studied in individuals with autism. This thesis sought to extend this work, and reports that subjective sensitivities are both present and cross-modal in a range of diagnoses and areas of neurodiversity, and in the general population. Similarities and differences in the nature of experience across groups is considered, and the implications for our understanding of mechanism are described. Throughout empirical chapters, the role and relevance of anxiety to the occurrence of subjective sensitivities is also explored, with results suggesting a possible pivotal role for somatic anxiety symptoms. Beyond characterizing these experiences, thematic analysis was also used to understand the impact of subjective sensitivities, and participants described varied and extensive effects upon daily functioning, personal relationships, and wellbeing. Exacerbating factors and associated coping mechanisms were also defined to ultimately support the need for enhanced understanding and support for sensory differences in clinical management (where appropriate) but additionally in educational, healthcare, and commercial settings. Finally, investigation into possible subtypes of subjective visual sensitivities using a novel self-report measure is described. Across four large samples, four highly replicable factors of visual sensitivity were found using bifactor modelling of the newly developed *Cardiff Hypersensitivity Scale (visual)*. This has clear implications for existing measures which often use only a limited number of items to assess what appears to be a multidimensional construct and provides a useful tool for future work to investigate causes and correlates of these experiences.

Contents

Acknowledgements

There are so many people that this thesis would not have been possible without. I plan to thank you all much more thoroughly, but until then:

The biggest thank you to Georgie and Petroc. Without overstatement, your support and mentorship has changed the course of my career. I feel very fortunate to have had such brilliant supervisors; your guidance, advice, and scientific training has been invaluable. Thank you for using the positions you have to empower and lift others, for your kindness, encouragement and reassurance, and for always cheering at the end of my presentations. Team CHYPS forever.

Thank you to my incredible family, with special mention to my mum and dad, for everything you've done to get me here – I am so grateful. And to my big sister Chloe, for always reminding me that it's just "one of them", and for being my fiercest supporter. With love always to Sherry and Shirley – two brilliant women who are so missed.

During the past three years, I've been lucky enough to have been in the academic orbit of some completely magical people; thank you to my Community, Charlie, Lauren, and Emma, for girl dinners and pub trips, and for being so generous with your time, love, and support. To Rebecca and Henry, for being beautiful, excellent people. To Tyler, an unbelievable late entry cheerleader, for keeping me laughing and for teaching me how to breathe. And to Josh, for all the hours spent at those desks, and for all the times we got each other through this – we made it!

A final thank you to Alice, Sian, Pooja, Claire, and Clarissa, for always being my home from home. You girls are easily one of the best things this university gave me. To Philippa, for everything, and to Finn, you are one of the best people to walk the planet, ever. Thank you for your unbounded kindness and support throughout this process, for always believing I could do this, and for always telling me so.

I am so thankful to know you all, and to have been given this opportunity. Thank you to everyone who helped along the way, and to Wellcome and Cardiff's School of Psychology for making it possible.

Chapter 1: General Introduction

We experience a range of sensory information throughout our daily lives, from the clothes we wear to the sounds of passing traffic, our existence is inherently sensory. For some, sensory stimuli can be experienced as distressing or distracting, leading to difficulties in engaging with the wider sensory world. These subjective sensory sensitivities can be cross modal; common precursors to the experience include bright or flickering lights, loud or repetitive noises, strong smells, and specific tactile (e.g., tags in clothing) or vestibular (e.g., being a passenger in a car) inputs. Subjective sensitivities are common to a range of clinical diagnoses and areas of neurodiversity (e.g., Engel-Yeger et al., 2013; Talay-Ongan & Wood, 2000; Ward et al., 2017) and are also reported in the general population (e.g., Robertson & Simmons, 2013). Reports of subjective sensory sensitivity show clear relationships to phenotypic severity (e.g., Lewin et al., 2015), and the prognostic value of identifying individuals high in subjective sensory sensitivity is increasingly recognised (e.g., Schwarzlose et al., 2023). Therefore, understanding subjective sensitivities, their measurement, impact, and mechanisms, has clinical and practical importance.

In this thesis, I investigate the nature of subjective sensory sensitivity, its impact on individuals experiencing it, and the role and relevance of the experience to different clinical diagnoses and areas of neurodiversity. To begin, Chapter 2 will explore subjective sensory sensitivity in migraine, specifically the extent to which the experience is mediated by symptoms of anxiety in this condition. Chapter 3 subsequently considers similarities and differences in subjective sensory sensitivities across diagnoses, and the implications of this for our understanding of mechanisms. In Chapter 4, a transdiagnostic approach is taken to investigate the impact of subjective sensory sensitivities for individual wellbeing and functioning, as well as considering first person insights into coping mechanisms and exacerbating factors. Finally, Chapters 5, 6, and 7 will describe the development of a novel measure of subjective visual sensitivities (*The Cardiff Hypersensitivity Scale*), including its psychometric properties, dimensionality, and relationship to relevant clinical symptoms.

What is sensory sensitivity?

It is important to be clear about terminology in defining and understanding subjective sensory sensitivity. Identical terms have been used to describe a variety of distinct

phenomena and mechanisms in the literature, which creates a challenge when evaluating the strength and nature of extant work. For instance, and likely due to its semantic ambiguity, the phrase 'sensory processing' has been used to describe aversive reactions to sensory stimuli (Engel-Yeger & Dunn, 2011b), variations in sensory threshold performance (Krauss et al., 2018), and also the brain's response to sensory information (Harriott & Schwedt, 2014), despite these being discrete phenomena. 'Sensory processing sensitivity' is also a described personality trait, argued to reflect a tendency for heightened sensitivity to a wide range of information, including sensory stimuli (noises, lights), but also aesthetic experiences, caffeine, pain and hunger signals, and other people's mood and feelings (Aron & Aron, 1997). As a result of this lack of clarity, describing an individual as having 'differences in sensory processing' could refer to vastly different constructs.

The inverse problem is also found, in which many different terms are used in the literature to refer to similar experiences. For example, to refer to first person reports of experiencing sensory information as aversive, existing work uses the following terms: subjective sensory sensitivity, sensory dysregulation, sensory over-responsivity, sensory hypersensitivity, atypical sensory modulation, sensory processing difficulties, exteroceptive sensory abnormalities, sensory hyperreactivity, and sensory intolerance (Bar-Shalita & Cermak, 2016; Dell'Osso et al., 2018; Houghton et al., 2020; Isaacs et al., 2020, 2022; Lewin et al., 2015; Ranford et al., 2020; Taylor et al., 2014; Ward et al., 2017). Many of these studies use the same questionnaire measures but differ in the terminology then used to describe their findings.

For clarity and to avoid this ambiguity, the descriptive framework used throughout this thesis will therefore differentiate between three forms of sensory sensitivity: subjective, behavioural, and neural (Ward, 2018).

Subjective sensory sensitivity refers to first person reports of experiencing sensory information as aversive, distracting, or overwhelming. Subjective sensory sensitivities can be cross modal, and common precursors to the experience include bright lighting, loud noises, light touch, and fast-paced sports (Brown & Dunn, 2002).

Behavioural sensory sensitivity instead relates to difference in detection or discrimination of sensory stimuli and can be measured through psychophysical threshold tasks (e.g., adaptive-staircase detection tasks; Schulz & Stevenson, 2021). Importantly, threshold

performance does not consistently associate with subjective reports of sensitivity (Schulz & Stevenson, 2021).

Finally, neural sensory sensitivity refers to the degree of neural activation in response to sensory input, measured via imaging approaches such as functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG).

What causes subjective sensory sensitivity?

Current theories of individual differences in subjective sensory sensitivity centre around increases in cortical excitability, relying largely on the assumption that neural and subjective sensitivities move together. Each defines neural sensitivity as increased for different reasons, including excitation/inhibition balance, differences in neural noise, and connectivity with wider brain regions. These theories will be very briefly outlined to provide theoretical context. The thesis does not directly address or differentiate these causal theories, but they will be discussed again in General Discussion in the light of the thesis findings.

Some theories of sensory sensitivity focus on the sparseness of the brain's representation of sensory input from an efficient coding perspective. GABA-mediated lateral inhibition is thought to underlie these sparse representations of sensory stimuli (Ward, 2018). An excess of excitation, or a lack of inhibition, would therefore lead to a stronger but less efficient neural response in response to sensory input, which might in turn be perceived as aversive.

Related theories focus on the predictability of sensory environments, from a statistical point of view. Neural representations are argued to be sparser when reflecting current predictions or previous perceptual history (which could be conceived as general expectation for what sensory worlds tend to be like). For instance, a key part of human perceptual history is natural scenes which we evolved to perceive. It is argued that the brain takes advantage of the statistical redundancy in these scenes. Stimuli which deviate from the statistical properties of natural scenes (e.g., those dominated by mid-high spatial frequencies) are reported to produce large, non-sparse responses in models of primary visual cortex (Hibbard & O'Hare, 2015). Many other forms of predictable stimuli also confer a reduced neural response (e.g., de Lange et al., 2018; Kok et al., 2012; Kumar, Kaposvari, & Vogels, 2017; Rummell et al., 2016). Relating this theory to subjective sensitivities, if an individual is less able to predict their

sensory environment, or make use of their perceptual history, the brain's response to sensory input would be increased, thus enhancing subjective sensitivities.

The relationship between neural activation in sensory regions and aversive experience is assumed in many theories but remains mechanistically unclear. For example, increased neural activity is described as eliciting metabolic stress, relating perhaps to a metabolic or physiological limit which some stimuli exceed (Hibbard & O'Hare, 2015; Wilkins, 2021), causing discomfort. Others instead relate feelings of discomfort or overwhelm to incompatibility between signals, such as sensations experienced when incompatible visual and vestibular signals are received (Gentile & Aguirre, 2020). Whilst these signals are not themselves harmful or exceeding any physiological capacity, discomfort occurs. Subjective sensitivities could therefore be how it feels for a human perceptual system to not be within its efficient processing range.

Further theories of subjective sensitivity focus on the relevance of neural noise, rather than signal. Specifically, increased endogenous noise, occurring both with and without a stimulus present, is argued to contribute to increased subjective sensitivity (explanation of why increased activity causes increased aversion is not provided; Ward, 2018). This theory provides a possible explanation for why perceptual hypersensitivity does not generally mean better threshold performance (behavioural sensitivity).

Finally, beyond neural activation in the sensory cortices, additional theories of subjective sensitivity consider hyperconnectivity to and from these areas (Ward, 2018). For example, the hippocampus is increasingly implicated in sensory prediction and integration of perceptual history, while functional connectivity with amygdala might be important for aversive experiences (Schwarzlose et al., 2023).

To summarise, sensory sensitivity is a broad term which encompasses first person experience, ability to detect or discriminate, and the brain's response to sensory input. The interaction between these constructs differs depending on the theoretical approach to subjective sensitivity, some of which are outlined above. Neural and subjective sensitivities are largely framed as moving together (although the extent to which neural over-activation in sensory regions causes the ongoing aversive experience is not yet well understood), and behavioural sensitivity is predicted to be enhanced or decreased depending on the extent to which activity reflects (processing of) signal or noise. It is important to note that many of these theories stem from work in autistic individuals, and this literature thus informs much of the

ongoing study in subjective sensitivity. The subsequent section will therefore summarise this work.

Subjective sensory sensitivity and autism

Autism is a developmental diagnosis characterised by difficulties with communication and social interaction, and restricted and repetitive behaviours. Sensory differences in autism include sensory sensitivities, but also hyposensitivities and sensory seeking behaviours (Ben-Sasson et al., 2019). Sensory differences have been associated with autism since its first description (Kanner, 1943), but were included as part of the condition's diagnostic criteria in the recent edition of the Diagnostic and Statistical Manual of Mental Disorders (defined as *"hyper-or–hypo-reactivity to sensory input or unusual interests in sensory aspects of the environment";* DSM-5, APA, 2013).

There is a rich field of work seeking to better understand the nature of these differences, their causes, and implications. This work finds sensory differences are cross modal and occur commonly in autism (in as many as 90% of autistic individuals; Leekam et al., 2007), with associations also found at trait level (Robertson & Simmons, 2013). Sensory differences relate to other key phenotypic characteristics of autism, being predictive of both social-communication differences (Kojovic et al., 2019) and repetitive behaviours (Schulz & Stevenson, 2019) in the condition, and also negatively associating with physical and psychological health (Lin & Huang, 2019). Sensory challenges are present across the lifespan, affecting functional abilities including eating (Cermak et al., 2010), sleeping (Mazurek & Petroski, 2015), and family life (Bagby et al., 2012) across schools (Gentil-Gutiérrez et al., 2021), workplaces (Khalifa et al., 2020), and healthcare settings (Samuel et al., 2022). In qualitative studies, individuals describe feelings of anxiety, distress, and physical discomfort as a result of sensitivities (Jones et al., 2003; MacLennan et al., 2022a; Robertson & Simmons, 2015), and quantitative work supports these effects on wellbeing (Lin & Huang, 2019; MacLennan et al., 2020; Syu et al., 2020). Given these effects, there is increasing awareness of the need to adapt public environments to better accommodate autistic individuals (MacLennan et al., 2022b; Tomczak, 2022).

It is easy to argue that our understanding of subjective sensitivity is most developed, notable, and evidenced in autism. In the previous decade, and particularly following its inclusion in diagnostic criteria, interest in and study of sensory differences in autism has

increased dramatically, involving thousands of autistic individuals (Ben-Sasson et al., 2019). Given the described impact of subjective sensitivities on the daily lives of individuals with autism, this is not unwarranted. However, autism is not the only diagnosis which associates with subjective sensitivities, but it is so dominantly associated with subjective sensitivities that it is frequently used as the benchmark to which other diagnoses are compared.

Subjective sensory sensitivity in neurodevelopmental and psychological diagnoses

Several other clinical diagnoses and areas of neurodiversity are associated with increased subjective sensitivities.

For instance, it is argued that atypical sensory experiences should also be conceptualised as a core feature of attention-deficit hyperactivity disorder (ADHD; Bijlenga et al., 2017). Increased hyper and hypo sensitivities are reported in children (Engel-Yeger & Ziv-On, 2011) and adults (Bijlenga et al., 2017) with ADHD. Given high levels of comorbidity between ADHD and autism (Ghanizadeh, 2012), it becomes important for study to tease apart the relative contributions of these diagnoses to the experience and extent of sensitivities. Indeed, evidence finds sensitivities are heightened in a dose-response relationship with ADHD (but not autistic) symptoms in adults with ADHD (Bijlenga et al., 2017). Likewise, the extent of subjective sensitivities in children with ADHD without comorbid autism has been found to be comparable in degree to children with autism (Dellapiazza et al., 2021).

This overlap presents a challenge for differential diagnosis, and additionally highlights the need for enhanced understanding of the nature and impact of sensitivities in this group. Extant literature finds subjective sensitivities associate with heightened anxiety (Engel-Yeger & Shimoni, 2023) and family stress (Rani et al., 2023), decreased participation (Engel-Yeger & Ziv-On, 2011), social quality of life (Engel-Yeger & Mevorach Shimoni, 2023), and functional impairment (Rani et al., 2023) in individuals with ADHD. Similarly, adjustments to both schools (Du Preez & Combrinck, 2022) and workplaces (Schreuer & Dorot, 2017) are increasingly recommended to improve the sensory environment for individuals with ADHD, further suggesting sensitivities are pervasive and impactful.

Subjective sensitivities are also found to be heightened in other neurodevelopmental diagnoses but are yet further under-represented in research outputs. Children with developmental co-ordination disorder (DCD), a neurodevelopmental diagnosis which affects physical co-ordination (APA, 2022), are reported to have increased sensitivities (Delgado-

Lobete et al., 2020), which associate with decreased everyday participation (Allen & Casey, 2017). Heightened subjective sensitivities are also reported in tic disorders (Isaacs et al., 2020, 2022), with some evidence that degree of sensitivity increases with comorbid diagnoses (Soler et al., 2019).

Moving beyond neurodevelopmental diagnoses, subjective sensitivities are found in several other clinical groups. Across eating disordered groups, heightened subjective sensitivities are reported in individuals with anorexia (Bell et al., 2017; Zucker et al., 2013), bulimia (Bell et al., 2017), and Avoidant/Restrictive Food Intake Disorder (ARFID; Dovey, Kumari, & Blissett, 2019; Pilato, 2021). It should be noted that, similarly to ADHD, comorbidity has particular relevance to sensitivities in eating disorders as autism is over-represented in ED populations (Huke et al., 2013). Associations with sensory sensitivities appear to persist independently, however.

For instance, Saure et al. (2021) reported that atypical sensory experiences are predictive of disordered eating symptoms and body mass index (BMI) in adults with anorexia, indicating that sensory differences relate to this diagnosis' phenotypic severity. This association remained after traits of autism were controlled for, and authors concluded that consideration of sensitivities in the support of individuals with anorexia is necessary. Sensory support for individuals with anorexia is not yet well studied, but initial hospital-based intervention to support sensory wellbeing in eating disorder services has received positive feedback (Tchanturia et al., 2022). Investigation in children with ARFID (without comorbid autism) also finds cross-modal subjective sensitivities to be heightened (Dovey, Kumari, & Blissett, 2019), and predictive of symptom severity (Pilato, 2021). Thus, across eating disorders which are separable in their symptomology, subjective sensitivities are observed.

Major affective disorders also show differences in sensory experience. In correlational studies, symptoms of depression are positively associated with subjective sensitivity (Serafini et al., 2017). In individuals with major depressive, bipolar, or schizophrenia spectrum disorders, sensitivities are increased and associate with poorer quality of life (Engel-Yeger et al., 2016; Paquet et al., 2022; Pfeiffer et al., 2014). Subjective sensitivity is also heightened in individuals with seasonal affective disorder (SAD) during both summer and winter periods, leading authors to propose a diathesis-stress model which includes sensory sensitivity as a key vulnerability to the condition (Hjordt & Stenbæk, 2019). Subjective sensitivity specifically to visual patterns has also been found to be predictive of depression (and anxiety) symptoms

3-months later, above the influence of related psychological constructs such as hopelessness and loneliness (Hui et al., 2022). This association is hypothesized to be due to common underlying mechanisms involving GABAergic inhibition, which is argued to predispose individuals to both visual sensitivity and mood disorders (Hui et al., 2022).

In trauma research, both number of traumatic events in childhood and formal diagnoses of post-traumatic stress disorder (PTSD) associate with increases in subjective sensitivity (Dowdy et al., 2020; Engel-Yeger et al., 2013; Serafini et al., 2016). PTSD symptoms also correlate with subjective sensitivity in a sample of veterans with and without mild traumatic brain injury (mTBI). However, sensitivity was further increased in those with mTBI compared to those without, even after controlling for symptoms of emotional distress, suggesting mTBI independently contributes to these forms of sensitivity (Callahan et al., 2018). In light of associations between trauma and sensory differences, recent work has acknowledged the comparatively small amount of empirical study in supporting the sensory needs of children who have experienced trauma, when compared to children with autism, and subsequently provided advice for sensory informed environmental planning to support these individuals in relevant settings (Robinson & Brown, 2016).

Finally, disorders of, and relating to, anxiety show enhanced subjective sensitivities. For instance, sensitivity is increased in both children and adults with obsessive compulsive disorder (OCD; Lewin et al., 2015; Rieke & Anderson, 2018), persists even when neurodevelopmental diagnoses are controlled for (Cervin, 2023), and directly relates to phenotypic severity (i.e., compulsions; Lewin et al., 2015). In cluster analyses using a non-clinical sample, a specific, sensory subtype of OCD was also proposed which is defined by a more severe symptom presentation (Ben-Sasson & Podoly, 2017). This aligns with preceding work in clinical samples, finding early-onset OCD to be associated with increased symptom severity, increased subjective sensitivities, and poorer treatment response (Rosario-Campos et al., 2001).

Sensitivities are also increased in panic disorder (Bossini et al., 2009) and social anxiety (Ludlow et al., 2015; Pickard et al., 2020). Relationships appear more complex when co-occurring autistic traits are considered, however; whilst Ludlow et al. (2015) report autistic traits to fully mediate the relationship between subjective tactile sensitivity and social anxiety, Pickard et al. (2020) instead describe (cross-modal) subjective sensitivities as mediating the

relationship between autistic traits and social anxiety. The specific relevance of autism to these experiences therefore remains unclear.

Subjective sensory sensitivity in physical health and other conditions

Aversion to sensory inputs is also relevant in physical health conditions. For example, migraine is characterized by recurrent, long-lasting, and intense headaches (International Classification of Headache Disorders 3rd Edition; ICHD-3, 2013). Photophobia (sensitivity to light) and phonophobia (sensitivity to sound) during a headache attack also form part of the diagnostic criteria for the condition (ICHD-3, 2013). There is limited literature investigating whether this sensitivity continues interictally and extends across sensory modalities. Genizi et al. (2019, 2020) have investigated sensitivities in children and adolescents with migraine, reporting increased (although not significantly different) subjective sensitivity scores. Significant differences were found in taste and smell sensitivity specifically, however. Sensory differences also associated with poorer quality of life in children with migraine (Genizi et al., 2019), aligning with evidence in other diagnoses (e.g., Lin & Huang, 2019). In adults, evidence of sensitivity is less clear. In an investigation of anomalous perceptual experiences in migraine, Horder et al. (2014) report participants with migraine to more frequently endorse items relating to subjective sensitivity; specifically, cross-modal sensory inputs were perceived as intense. Conversely, Marca et al. (2023) report differences in sensitivity only in the visual modality, aligning with evidence of reduced visual discomfort thresholds in interictal periods (Woodhouse, & Drummond, 1993). Leveque et al. (2020) found that sensitivity to light, sounds, and smells was increased in people in migraine, although other sensory modalities were not considered in this work. Taken together, this literature is consistent with heightened interictal subjective sensitivities in migraine, although the extent of cross modal sensitivities is not yet clear.

Cross modal sensitivities have also been considered in other diagnoses which are classically associated with sensitivity in specific senses, as is the case in migraine. For example, persistent postural perceptual dizziness (PPPD) is a neuro-vestibular disorder characterized by chronic dizziness triggered by motion (active or passive) and intense visual environments (e.g., supermarkets, busy traffic, cinemas; Bronstein, 1995). Despite the centrality of vestibular and visual input to the disorder, recent work finds PPPD to be associated with subjective sensitivity across all senses (Powell et al., 2020b).

Finally, there is evidence to suggest high subjective sensitivity is also present in a range of other diagnoses including epilepsy (Shahar et al., 2013), dyslexia (Estaki et al., 2021), functional neurological disorder (Ranford et al., 2020), fibroymyalgia (Ten Brink & Bultitude, 2022; Wilbarger & Cook, 2011), and synaesthesia (Ward et al., 2017).

Subjective sensory sensitivity as a transdiagnostic symptom

Overall, the common occurrence of subjective sensitivity across diagnoses is clear, as is its relationship to phenotypic severity (e.g., Engel-Yeger et al., 2018; Lewin et al., 2015; Tavassoli et al., 2012), quality of life (e.g., Costa-lópez et al., 2021; Engel-Yeger & Dunn, 2011a; Genizi et al., 2019; Lee, 2012; Pfeiffer et al., 2014), and potential prognostic value (e.g., Hui et al., 2022).

Of interest is the theoretical stance taken by different aspects of the sensitivity literature reviewed thus far. As described, and likely due to the centrality of sensory differences to the diagnosis, many researchers use autism as a lens through which to view or interpret the sensitivities of other conditions. For instance, considering whether ADHD and autism show comparable sensitivities (Dellapiazza et al., 2021), or defining sensitivities as a shared feature between a given diagnosis and autism (Ward et al., 2017). This tendency for comparison appears to be less common in physical health diagnosis such as migraine and functional neurological disorders, although scores on questionnaire measures for these conditions are often comparable to those of adults with autism (Ranford et al., 2020).

Arguably, there is a need to move beyond this approach. Although research into subjective sensitivities is most common in autistic populations, the evidence reviewed thus far clearly defines subjective sensory sensitivity as a transdiagnostic experience. To assume that sensory sensitivity has a specific relevance to autism, rather than being a broader construct that contributes to a range of diagnoses, may limit development of theories about the mechanisms underlying the experience. Taking a broad, transdiagnostic approach also raises the previously unconsidered question of whether sensory sensitivities are qualitatively different or similar across people with different conditions.

Comorbidities, and the role of anxiety

The transdiagnostic nature of subjective sensitivity necessitates that research which seeks to better understand the experience should consider the role of comorbid diagnoses.

Given the enhanced awareness and empirical study in the condition, autism and corresponding traits are often controlled for in research of this kind, particularly with conditions with high comorbidity, including ADHD (Dellapiazza et al., 2021) and eating disorders (Saure et al., 2021).

However, anxiety symptoms are often not consistently integrated into statistical investigation of subjective sensitivities in different diagnoses. This is despite comorbidity with all conditions described above including autism (Rosen et al., 2018; Zaboski & Storch, 2018), ADHD (Schatz & Rostain, 2006), DCD (Hill & Brown, 2013), eating disorders (Martín et al., 2019; Nicely et al., 2014), depression (Tiller, 2013), migraine (Breslau, Davis, & Andreski, 1995), epilepsy (Gurgu et al., 2021), functional neurological disorder (Pun et al., 2020), PPPD (Popkirov et al., 2018), and synaesthesia (Carmichael et al., 2019). Symptoms of anxiety also demonstrate strong and consistent associations with subjective sensitivity (Carpenter et al., 2019; Engel-Yeger & Dunn, 2011b), to a greater extent than depression which is also a common comorbidity (Schwarzlose et al., 2023).

There are several possible explanations for the association between anxiety and sensory sensitivity. For instance, it could be the case that sensitivity is caused by, or is a symptom of, anxiety, as discussed by Green & Ben-Sasson (2010). Investigations of attention bias suggest that anxious individuals have increased hypervigilance to their environment, and subsequent difficulty disengaging their attention from a threat relevant stimulus, even when instructed to (Mobini & Grant, 2007). It is possible that these hypervigilance states associated with anxiety therefore increase the likelihood that sensory stimuli in the environment is noticed, with a tendency to perceive stimuli as threatening heightening the aversive reaction, and a reduced ability to disengage attention from the stimulus further exacerbating the sensitivity. An enhanced response to sensory stimuli can then be further strengthened through interoceptive conditioning, whereby a conditioned stimulus (aversive sensory input) is paired with the uncomfortable physiological reaction. Avoidance of stimuli that elicit this response further reinforces the conditioned response, ultimately leading to enhanced environmental scanning, and increased reaction to sensory stimuli when detected. This theory would impose a unidirectional relationship, whereby anxiety precedes and predicts subjective sensitivity. However, cross-sectional research is not able to elucidate these effects, and study using longitudinal or causal design is limited.

One such study by Schwarzlose et al. (2023) found that sensory sensitivities in children were predictive of increased anxiety at one-year follow up, even after controlling for autistic traits and psychiatric symptoms. Similarly, Green et al. (2012) assessed the anxiety and sensory sensitivities of toddlers with autism at two time points, finding that when controlling for anxiety at time 1, sensory sensitivities predicted anxiety at time 2. The inverse effect (where anxiety predicts sensitivity) was non-significant, providing evidence against the theory that anxiety is causal in the development of sensory sensitivities. Finally, Carpenter et al. (2019) reports that symptoms of sensitivity during preschool is predictive of school-age anxiety symptoms, even when preschool anxiety and other psychiatric diagnoses were controlled for. These authors therefore argue that sensory sensitivities precede anxiety and provide unique information on psychiatric risk in children.

One mechanism through which sensory sensitivities could lead to the development of anxiety is via context conditioning. If an unconditioned stimulus (e.g., aversive sound) is not consistently predicted by the conditioned stimulus (i.e., an unexpected, loud sound could occur from several different types of objects), then the fear response can broaden from being triggered by a specific object, to an entire context. This could explain the avoidance of settings such as restaurants and supermarkets (Pfeiffer et al., 2014), as well as of specific objects (Zhang et al., 2023), by people with heightened sensitivity. The avoidance, hypervigilance, and corresponding physiological arousal resulting from aversive reactions to sensory stimuli is argued to lead to generalized symptoms of anxiety (Green & Ben-Sasson, 2010). This aligns with Hofmann's model of mood disorders (Hofmann et al., 2012), whereby emotion regulation strategies (i.e., avoidance) in response to aversive feelings contribute to the development of anxiety, and is supported by mediation analyses (McMahon et al., 2019). Other cross sectional study also describes the role of other cognitive traits (e.g., intolerance of uncertainty; Panchyshyn et al., 2023; Uljarević et al., 2016) as contributing to these relationships. However, further study which assesses directions of effect and uses causal design in adults specifically is needed.

It is also possible that the association between subjective sensitivity and symptoms of anxiety is not causal but driven by a common risk factor. For example, the amygdala has been associated both with differential activation in anxiety disorders (Shin & Liberzon, 2010) and with distinct patterns of connectivity in individuals with increased subjective sensitivity (Schwarzlose et al., 2023). Similarly, GABAergic systems are a therapeutic target in

anxiety (Möhler, 2012), with existing pharmaceutical intervention acting via the facilitation of GABA inhibition (Farach et al., 2012). The role of GABA and inhibitory processes is also implicated in heightened sensory sensitivity (Edden et al., 2009; Orekhova et al., 2019; Stroganova et al., 2015). It is therefore possible that differences in neural activation or circuitry underlie both anxiety and subjective sensitivity, conflating them as causal.

Another non-causal possibility, as outlined by Green and Ben-Sasson (2010), is that associations between the two constructs are driven by diagnostic overlap. Anxiety and subjective sensitivity show similarities in their physiological and behavioural responding, including avoidance and fear of the physical environment, negative affect, and hyperarousal (e.g., Reynolds et al., 2010; Vreeburg et al., 2010). Many self-report measures of subjective sensitivity also do not necessarily distinguish between responding as a result of anxiety versus sensory sensitivity specifically. For instance, one item from the Adolescent/Adult Sensory Profile (AASP; Brown, & Dunn, 2002), a commonly used measure, asks "I move away when others get too close to me". It is possible that an individuals high in social anxiety might endorse this item, despite not necessarily experiencing the high subjective tactile sensitivity which this item is assessing. The use of these measures to study the association between anxiety and sensitivity is therefore more challenging.

Context is also important to this distinction. For example, occupational therapists frequently work within sensory frameworks and assess sensory sensitivities, whilst psychologists commonly assess anxiety and associated disorders. In a study which asked individuals from both disciplines to rate items taken from anxiety and sensory scales for the extent to which they represented anxiety or sensory disorders in toddlers, occupational therapists were more likely to rate items as sensory in nature, and several items were rated as indicators of both conditions (Ben-Sasson et al., 2007). In vignette case studies, 50% of occupational therapists diagnosed over-responsivity in a case representing generalized anxiety, whilst 92% of psychologists identified an anxiety disorder. Similarly, when sensory sensitivity was represented, all occupational therapists identified sensory differences whereas 26% of psychologists diagnosed an anxiety disorder. This highlights the overlap between anxiety and subjective sensitivities in existing measures and observable behaviours, although the generalizability of this finding beyond toddlers where self-report is more challenging has not been determined. It does however suggest a need for more consistent and differential

understandings of subjective sensitivity and anxiety, to aid in our understanding of their relative (or associated) causes.

Measuring subjective sensory sensitivity

Self-report measures of subjective sensory sensitivity are varied in the literature. There is a tendency for some empirical work to make use of questions which are not validated, but created specifically for the study (e.g., Lévêque et al., 2020), or created using a selection of items from existing measures (e.g., Wilbarger & Cook, 2011). Without formal piloting or psychometric investigation, the validity or reliability of these questions are somewhat limited.

However, many studies utilise well-validated questionnaires in their investigations. For example, the AASP is a self-report measure of subjective sensory experiences, and is reportedly the most commonly used assessment measure in studies investigating sensory differences in autism (DuBois et al., 2017). The measure assesses sensory experience as it relates to Dunn's model of sensory processing (Dunn, 1997). This theoretical model conceptualises sensory differences along two continua: neurological threshold and behavioural response. Neurological threshold is argued to represent the amount of stimuli necessary for a neuron to respond to sensory input (i.e., low threshold = very little stimuli required for a neuron to respond). Behavioural response refers to the strategies used alongside an individual's threshold (passive vs active). Passive strategies align with the threshold. Where thresholds are high, stimuli would tend not to be noticed, whereas when they are low, more stimuli would be noticed. Active strategies instead work against the threshold, meaning when thresholds are low, sensory stimuli are sought out, and when thresholds are high, they are avoided. Four 'quadrants' represent the possible combinations of these threshold and behavioural response continua.

Importantly, formal description of the measure's development does not provide evidence that subjective responses to the questionnaire's items relates directly to neural response or threshold. Research employing the AASP therefore varies in the extent to which it subscribes to this theoretical model, and many studies do not frame AASP scores as representing neurological threshold.

Other measures similarly conflate behavioural and subjective sensitivities. For example, the Sensory Perception Quotient uses several items which arguably centre on (assumed) threshold differences (e.g., *"I notice the flickering of a desktop computer even*

when it is working properly"). This calls into question the understanding of subjective sensitivity across empirical work. Although threshold differences are relevant to our understanding of the cause of sensory differences (Ward, 2018), subjective sensory sensitivity is a distinct concept. An individual who notices a flickering computer screen might remain entirely unbothered by it, for example, whilst someone with high subjective sensitivity might find this uncomfortable or even unbearable to look at. Measures which focus only on detection or discrimination differences may not adequately distinguish these experiences, and conclusions drawn from extant work should consider these distinctions.

Another increasingly commonly used measure is the Glasgow Sensory Questionnaire (GSQ; Robertson & Simmons, 2013). The GSQ assesses both hypo- and hyper-sensitivity across sensory modalities, with equal item distributions. It does not have a specific underlying theoretical model; however, it was developed using indicators of sensory differences in autism as reported by parents and in the wider literature. Therefore, although it has been used in general population samples (Robertson & Simmons, 2013), the authors acknowledge that the questionnaire is biased towards sensory features found in autism. The extent to which these features represent sensory experiences in the general population, or indeed other clinical diagnoses and areas of neurodiversity, is not yet known.

There are several other questionnaires designed to assess sensory differences. Some focus specifically on autism (e.g., Sensory Experiences Questionnaire; Baranek et al., 2006, Sensory Sensitivity Questionnaire; Talay-Ongan & Wood, 2000), some are developed in the context of autism but are applicable to other populations (e.g., Sensory Perception Quotient; Tavassoli et al., 2014), whilst others are developed for use in any population (e.g., SensOR Scale; Schoen et al., 2008, Sensory Hypersensitivity Scale; Dixon et al., 2016).

It is worth noting here other theoretical positions that have aligned themselves with subjective sensitivities, including that of the 'sensory processing sensitivity'. Sensory processing sensitivity is a personality trait, argued to reflect a tendency for heightened sensitivity to a wide range of information, including sensory stimuli (noises, lights), aesthetic experiences, caffeine, pain and hunger signals, and other people's mood and feelings. The Highly Sensitive Person Scale (HSPS) is a self-report measure of this trait; original work described it as unidimensional (Aron & Aron, 1997), however subsequent studies find that questions related to sensory sensitivity may form their own factor (Ershova et al., 2018).

Regardless of the measure's dimensionality, the HSPS highlights a lack of clarity surrounding the term 'sensitivity' within the field, and the need for specificity in measurement approaches.

Qualitative exploration of sensory sensitivities

Beyond quantitative study, qualitative explorations of the nature and impact of subjective sensitivities is limited and largely takes place with autistic individuals. For example, Robertson and Simmons (2015) conducted a focus group with adults with autism, and described the types of stimuli which participants found problematic, how it made them feel, and circumstances that worsened the experience. Participants described that discomfort from the same sensory input would be reduced when they had control over it; control in this instance included actively engaging with it themselves, being able to reduce it (e.g., by wearing earplugs), or knowing an input was coming. Predictability was also recognised in recent work which identified the types of public environments which present sensory challenges to autistic adults and described associated principles which can affect individual ability to engage with these spaces (MacLennan et al., 2022b). Predictability was one such principle, along with other aspects of the environment such as its degree of sensory burden and whether there is opportunity to recover from sensory challenges.

Autistic participants in several studies have also described how their emotional state prior to an aversive sensory input impacts their ability to engage with it; for instance, if stressed or anxious prior to an exposure, participants could tolerate it less (e.g., MacLennan et al., 2022a; Robertson & Simmons, 2015; Smith & Sharp, 2013). Smith and Sharp (2013) further explained how sensory events can worsen this existing stress, creating a vicious cycle where sensory inputs are increasingly intolerable. Other qualitative study in autistic individuals has also focused on how sensitivities affect engagement in the classroom (Howe & Stagg, 2016), family dynamics (Daly et al., 2022), and pregnancy and childbirth (Samuel et al., 2022). Overall, this work defines negative sensory experiences as impactful in the day-to-day life of individuals with autism.

Qualitative study in other diagnoses, although limited, describes similar effects. For example, individuals who have experienced stroke (Alwawi et al., 2020) or acquired brain injury (de Sain et al., 2023) describe increased fatigue, feelings misunderstood by others, changes in their ability to engage in daily occupations, and anxiety or irritation in response to overwhelming sensory information. The nature of problematic sensory stimuli and associated

coping mechanisms (e.g., avoidance) has also been qualitatively investigated in individuals with ADHD (with particular focus on occupation; Schreuer & Dorot, 2017), other neurodevelopmental diagnoses (Wada et al., 2023), and the general population (Robertson & Simmons, 2018).

In sum, both qualitative and quantitative work highlights associations between subjective sensitivities and various aspects of personal wellbeing. Much of this study has either been in autistic individuals, or interpreted through the lens of autism (e.g., Robertson & Simmons, 2018), meaning there is scope for further first person insights into the ways in which sensitivities impact daily life in other, more diverse samples. This would be beneficial in supporting and implementing adaptations to public spaces, or informing therapeutic intervention, which could contribute to making exposure to sensory environments more manageable.

Visual sensitivity: definition and overview

Subjective sensory sensitivities occur cross-modally, however, to narrow the scope of the PhD, Chapters 5 to 7 focus primarily on visual hypersensitivity. Visual sensitivities are experienced in response to a range of stimuli, including bright, flickering, or fluorescent lighting, strong colour, patterns, and motion (e.g., MacLennan et al., 2022a; Parmar et al., 2021; Robertson & Simmons, 2015, 2018; Wada et al., 2023). Visual (hyper) sensitivity, being a perceptual experience, is defined in terms of either self-report questionnaires, or rating of discomfort in response to stimuli. Again, we make the distinction here between subjective sensitivity and sensitivity in detection, discrimination, or neural response.

Visual sensitivity: causes

Beyond the general theories outlined in the first part of this chapter, there are also areas of focus within the literature. For example, specific aversion to light (termed photophobia; Digre & Brennan, 2012) or to high contrast, mid-high spatial frequency patterns (termed visual stress or visual discomfort; Wilkins, 1995). With these specific areas of focus comes more specific theories of mechanism that are both retinal and cortical in nature.

One hypothesis of photophobia centres around intrinsically-photosensitive retinal ganglion cells (ipRGCs), which are specialized cells containing the photopigment melanopsin,

allowing them to respond to light stimuli (Digre & Brennan, 2012). Individuals with migraine who became blind due to degeneration of rods and cones, yet continued to experience light sensitivity, implicated ipRGCs in photophobia (Noseda et al., 2010). However, ipRGCs are particularly sensitive to blue light, and individuals with migraine show enhanced sensitivity to blue, white, red, and amber lights, which suggests causes of photophobia are not limited to these cells (Wilkins et al., 2021).

Beyond ipRGCs, and the probable influence of rods and cones (e.g., see Wang et al., 2022), neural response in sensory regions is also a relevant mechanism. Cortical theories of photophobia centre on hyperexcitability of the visual cortex in response to light, drawing on evidence which reports increased BOLD activation in individuals with photophobia when compared to controls (Malecaze et al., 2001). Recent work has extended this to other forms of visual sensitivity; for instance, Wilkins et al. (2021) argue that hyper-excitability can explain visual sensitivity experienced interictally in migraine, including aversion to flicker, patterns, and colour. These aversive stimuli all produce large haemodynamic responses in visual cortex (e.g., Bargary et al., 2015; Chouinard et al., 2012), with differential patterns of hyperexcitation argued depending on the nature of aversion. Associated feelings of discomfort are thought to reflect a homeostatic response which lessens the potential cost of hypermetabolism (Wilkins et al., 2021), or the potential for light-induced retinal damage (Hunter et al., 2012). Importantly, although Wilkins et al. propose hyperexcitability as a mechanism for interictal visual sensitivities in migraine specifically, it is acknowledged that this homeostatic mechanism could also vary in severity in the general population.

In the General Discussion I will return to these theories in the light of the different factors of visual hypersensitivity revealed in Chapters 5 to 7.

Visual sensitivity: measurement

Self-report questionnaires of visual sensitivity often focus on specific aspects of the experience. For example, the Visual Discomfort Scale (Conlon et al., 1999) largely focuses on discomfort when reading (e.g., "*When reading, do you ever unintentionally re-read the same words on a line of text?"*), and includes few questions about discomfort in response to pattern, and the Leiden Visual Sensitivity Scale (L-VISS; Perenboom et al., 2018) includes items relating to bright or flickering lights and patterns, with particular focus on afterimages and blurred vision. Measures of photophobia include the Photosensitivity Assessment

Questionnaire (Bossini et al., 2009; Bossini, Padula, & De Capua, 2006), the Utah Photophobia Symptom Impact Scale (UPSIS-17; Cortez et al., 2019, 2023), and a photophobia scale for use in migraine (Choi et al., 2009).

Measures of subjective sensory sensitivity more broadly also include questions relating to visual sensitivities. However, they tend to be similarly limited in the aspects of sensitivity they assess. For example, both the AASP and Sensory Sensitivity Scales (SeSS; Aykan et al., 2020) do not assess sensitivities to pattern and reading, despite these being known complaints in the literature and a key feature of visual stress (e.g., Parmar et al., 2021). Similarly, the GSQ includes only three questions assessing visual hypersensitivities, focused on bright lights, flicker, and noticing small visual stimuli in the environment. The limited range of items included in these measures has implications for our understanding of sensitivity to different visual features, and their causes and prevalence across diagnoses.

Other stimuli-based measures ask participants to rate their discomfort in response to images, patterns, or light. For example, the Pattern Glare Test (Evans & Stevenson, 2008; Wilkins, 1995) asks individuals to rate the discomfort and associated distortions they experience in response to three, achromatic gratings which differ in their spatial frequency (low; approx. 0.7cpd, medium; approx. 3cpd, high; approx. 11cpd). Increased discomfort scores on the Pattern Glare Test are found in individuals with migraine (Harle et al., 2006), synaesthesia (Ward et al., 2017), depression (Qi et al., 2019), and associate with high schizotypy (Torrens et al., 2023) and out of body experiences (Braithwaite et al., 2013) in the general population. Similar tasks include instead asking participants to view images known to elicit high discomfort due to their statistical properties, which deviate from those found in natural scenes (Penacchio et al., 2021). For example, Powell et al. (2021) found individuals with PPPD (or with more PPPD symptoms) reported heightened discomfort to these static images. Exposure to aversive stimuli is similarly used in investigation of photophobia, where visual discomfort thresholds are determined by the lowest luminance level needed to induce discomfort (Pinheiro et al., 2020).

Of note, reports of discomfort to these stimuli do not consistently associate with subjective, questionnaire reports of visual sensitivities (e.g., Ward et al., 2017). This is problematic given different measures should theoretically be capturing the same concept of visual sensitivity. It is possible that this is because these methods focus on only one feature of

visual stimuli (e.g., spatial frequency), which differ from aspects of visual sensitivity assessed by questionnaire measures (e.g., GSQ does not assess aversion to pattern).

Summary

Individuals with high subjective sensory sensitivity report aversion, distraction, or overwhelm in response to a range of everyday sensory stimuli (e.g., Brown, & Dunn, 2002; Robertson & Simmons, 2013). This experience is classically associated with autism (APA, 2022), however there is evidence to suggest sensitivities exist across diagnoses and areas of neurodiversity (e.g., Engel-Yeger et al., 2013; Isaacs et al., 2020; Ward et al., 2017). Beyond association, subjective sensitivities may also be important in developing our ability to predict risk or understand prognosis (e.g., Qi et al., 2019; Schwarzlose et al., 2023). Given known associations between sensitivities and quality of life (e.g., Pfeiffer et al., 2014), there is also a need to move beyond clinical samples to understand how sensitivities may also impact the general population, with a view to informing adjustments and intervention which could make the sensory world more tolerable for all. Enhancing our understanding of subjective sensitivities therefore has theoretical, clinical, and practical value.

This thesis will investigate some of the outstanding questions in the sensitivity literature. Chapter 2 considers subjective sensory sensitivities in migraine; specifically, whether sensitivities to light and sound which form part of the diagnostic criteria (ICHD-3, 2013) exist interictally and also across senses. Given described associations with anxiety (e.g., Engel-Yeger & Dunn, 2011b), this chapter will also employ a formal mediation model to determine whether anxiety symptoms can explain sensitivities in this diagnosis. Chapter 3 begins to consider cross-condition differences in subjective sensitivities, using existing questionnaire measures to understand how cross-modal sensitivities present, and the role and relevance of comorbid diagnoses. Chapter 4 subsequently takes a qualitative, diagnosis-agnostic approach to investigate how sensitivities affect daily life and wellbeing, and how they are coped with. The remaining chapters consider subjective visual sensitivities in more detail. Based on existing work and insights provided by Chapter 4, Chapters 5 and 6 describe the development and psychometric investigation of a novel self-report measure of visual sensitivities. These analyses determine that visual sensitivities are not unidimensional, but instead four factors of visual sensitivity can be consistently and reliably identified. Finally, Chapter 7 explores how clinical diagnoses associate with each of these four factors and

investigates how specific symptoms of anxiety may contribute to the development or maintenance of these experiences.

It should be noted that throughout this work, the nature of subjective sensitivities is considered across clinical diagnoses and areas of neurodiversity. Terms diagnosis and condition are at times used interchangeably, but with recognition that in this context, a medical model or approach is not necessarily endorsed.

Chapter 2: Price, A., Sumner, P., & Powell, G. (2021). Subjective sensory sensitivity and its relationship with anxiety in people with probable migraine. *Headache: The Journal of Head and Face Pain*, *61*(9), 1342-1350.

Introduction

Migraine attacks are typically characterised by enduring headache, nausea and sensitivity to light, sound and odours (ICHD-3, 2013). Sensory stimuli can also trigger or worsen attacks (Borini et al., 2011; Friedman & De Ver Dye, 2009) and sensory disturbances (most often visual) commonly occur in those who experience migraine with aura (Russel & Olesen, 1996).

In the present chapter we investigate whether differences in sensory experience exist in people with migraine *between* attacks (also known as interictal differences). As described in the General Introduction, it is important to distinguish two meanings of 'sensitivity': heightened sensory experience or measured thresholds for detecting or discriminating sensory stimuli. These two meanings are not straightforwardly related.

There is some evidence that between attacks, people with migraine show different threshold sensitivity to stimuli compared to people without migraine. The evidence is mixed; for example, both higher and lower sensory thresholds have been reported across modalities (Harriott & Schwedt, 2014). However, threshold performance does not predict the strength or quality of self-reported sensory experience (Schulz & Stevenson, 2020), highlighting a need to clearly distinguish between these two concepts. Threshold measurements are thought to tap the basic capabilities of early processing, while the subjective experience involves extensive activation and feedback well beyond the primary sensory cortices (Ress & Heeger, 2003). Given that subjective sensory experience is associated with reduced wellbeing (Ben-Avi et al., 2012; Engel-Yeger & Dunn, 2011a) and anxiety (Engel-Yeger & Dunn, 2011b), understanding whether sensory experiences differ in migraine remains important whether or not threshold differences are confirmed.

Evidence from children and adolescents with migraine has shown increases in self- or parent-reported sensory behaviours, which may indicate heightened subjective sensitivity to sensory information (Genizi et al., 2019, 2020). In children, this reported hypersensitivity was associated with reductions in quality of life.

Furthermore, work investigating the presence of psychotic symptoms and hallucinations in migraine has also found evidence of subjective sensitivity (Shepherd &

Patterson, 2020). Although the self-report measure used in this study was not a direct measure of sensory sensitivity, people with migraine more frequently endorsed items relating to a heightened experience of sensory stimuli when compared to people without migraine.

Finally, in an investigation of the relationship between subjective sensory sensitivity and attention in migraine, Leveque et al. (2020) recently found that adults with migraine self-reported increased sensitivity to light, sounds and odours between attacks when compared to people without migraine. Sensory sensitivities were correlated with self-reported attentional difficulties, but not migraine disability.

Taken together, this literature is consistent with the idea that migraine is associated with interictal differences in subjective sensory experience. However, an additional consideration in investigating sensory experience in migraine is the experience of anxiety. Anxiety is found to commonly co-occur with migraine at both trait and clinical levels (Breslau et al., 1991; Fuller-Thomson et al., 2017; Mongini et al., 2003; Smith et al., 2003), and the two conditions might share genetic predispositions (Gonda et al., 2007), neurotransmitter systems (Noseda et al., 2014), and psychological influences (e.g. interoceptive conditioning; Smitherman et al., 2013). Anxiety is also associated with sensory hypersensitivity in people without migraine (Engel-Yeger & Dunn, 2011b). It is therefore possible that if differences in sensory experience exist in migraine, they could be driven (at least in part) by heightened levels of anxiety.

It is worth noting that Leveque et al. (2020) did not find that anxiety explained differences in sensory processing that they observed. In fact, they did not find that anxiety and sensory sensitivities were correlated at all in their sample. Therefore, the triadic relationship that may exist between migraine, sensory experience, and anxiety has not been well characterised in the literature so far and could be addressed by using more formal mediation analyses with a larger pool of participants. Given differences in anxiety and subjective sensory sensitivity could have relevance for the day-to-day experiences of individuals with migraine, these effects are worth being fully explored.

In the present study, our aim was therefore to better characterise differences in interictal sensory experience in migraine. We did this by: 1) using an established questionnaire of subjective sensory sensitivity that is underpinned by theory and spans the range of sensory modalities, 2) describing the relationship with anxiety more comprehensively using a formal mediation model, 3) exploring the individual and unique contribution of different sensory

modalities, and 4) using a large community sample of 117 individuals with migraine, and 827 comparison participants without migraine.

The sensory experience questionnaire we used was the Adolescent/Adult Sensory Profile (AASP; Brown & Dunn, 2002). The AASP was the most appropriate for our study; unlike other similar measures, it is designed for general population use and provides a measure of subjective sensory experience across six sensory modalities (taste/smell, visual, auditory, tactile, movement and activity). We were interested in two sub-scales of the AASP that indicate subjective sensory hypersensitivity: sensory sensitivity and sensory avoidance. Despite its common use in sensory processing literature, the AASP is yet to be used in adult migraine populations, the absence of which has been noted (Ward, 2018). To explore the relationship between sensory experience, migraine and anxiety, we also collected data on anxiety, using the Hospital Anxiety and Depression Scale (Zigmond & Snaith, 1983).

We hypothesised that migraine would be associated with increased subjective sensory sensitivity and avoidance across all modalities, and this relationship would be mediated by symptoms of anxiety. We speculated that vision might be the dominant sense driving these relationships, because it is commonly associated with migraine aura and triggers (Friedman & De Ver Dye, 2009; Russel & Olesen, 1996).

Methods

Participants

Participants were recruited from the community via two methods. The first involved emailing participants from a community health list with an advert to participate in a survey. The advert described the broad interest in dizziness (the findings of which relate to another study; Powell et al., 2020a), sensory sensitivity and migraine held by the researchers, whilst emphasising the desire for a range of participants regardless of experience with topics of interest, excluding only those under 18. Approximately 2500 responses were received (of 18,683 email addresses used); 465 participants had missing data for the AASP, whilst 1379 had missing anxiety data. Analyses therefore only included those with complete data for all measures of interest (n = 818). Participants were aged between 19 and 86 (Mean = 57.0, SD = 13.8) and 604 (74%) were female. Median reported education attainment was 3, where 0 = no education, 1 = GCSE/O Level, 2 = A-level/BTEC, 3 = Undergraduate, 4 = Postgraduate.

The second recruitment method utilised the website Prolific Academic, on which the public can participate in surveys and receive compensation. Participants were compensated £5 for the survey. Of 214 responses received, 14 had missing AASP data, whilst 74 had missing anxiety data. A total of 126 participants returned valid and complete responses for each measure and were therefore included in analyses. Participants were aged between 18 and 54 (Mean = 26.8, SD = 6.8), and 35 (28%) were female. Median educational attainment was 3.

The final combined sample therefore consisted of 944 participants aged between 18 and 86 (Mean = 53.0, SD = 16.6), 639 of which were female (68%). Cardiff University's School of Psychology ethics committee provided approval for all procedures. Participants read a consent form online, before providing electronic informed consent via an on-screen tick box.

This is an *a priori* secondary analysis of collected data, which was primarily analysed to answer questions concerning visually-induced dizziness (Powell et al., 2020a, 2020b). The sample size was based upon available data; no statistical power calculation was conducted prior.

Measures

All questionnaires were delivered online via Qualtrics. Demographic information and details of currently diagnosed vestibular disorder (details provided in *Appendix A*) was collected.

Migraine Screening Questionnaire (MS-Q; Láinez et al., 2005): The MS-Q includes five items which ask individuals about migraine episodes experienced in their lifetime, each with a yes/no response. Participants reporting four or more 'yes' responses were categorised as having probable migraine. Example items include "Do you usually suffer from nausea when you have a headache?" and "Does light or noise bother you when you have a headache?". The MS-Q shows adequate validity and reliability (Cronbach's α=0.82; Láinez et al., 2005).

Adolescent/Adult Sensory Profile (AASP; Brown, & Dunn, 2002): The AASP is a 60-item self-report measure of sensory function as it relates to Dunn's model (Dunn, 1997). Of four possible subscales, we were only interested in the sensory sensitivity and sensory avoidance subscales. Both subscales are argued to indicate subjective sensory sensitivity but refer to different behavioural reactions to sensory input. Whilst the sensory sensitivity subscale

represents a dislike for sensory stimuli and distractibility in its presence (e.g., "I'm uncomfortable wearing certain fabrics"), sensory avoidance indicates behaviours which limit exposure to stimuli and restrict unpredictability (e.g., "I avoid or wear gloves during activities that will make my hands messy"). Higher subscale scores indicate greater levels of the corresponding sensory behaviour. The AASP quadrants have been found to have moderate to good internal consistency (Cronbach's α between 0.66 and 0.81) and construct validity (Brown & Dunn, 2002; Brown et al., 2001).

Subscales remained separate for initial analyses; however, for ease of interpretation, and due to their high collinearity (r = .78), sensory sensitivity and sensory avoidance subscales were combined into a single variable (referred to as 'subjective sensory sensitivity') for mediation analysis.

Items of the AASP assess sensory processing across six modalities: taste/smell, visual, auditory, tactile, movement and activity. As in previous work (Schulz & Stevenson, 2021; Schulz & Stevenson, 2020), modality specific subscales were also calculated to explore the relative influence of sensory sensitivities in each domain upon migraine. This involved summing items from both sensory avoidance and sensory sensitivity subscales according to their associated modality.

Hospital Anxiety and Depression Scale (HADS; Zigmond, & Snaith, 1983): The HADS is a 14-item measure assessing symptoms of depression and anxiety. Individuals are asked to indicate the frequency they experience each item, on a four-point scale (e.g., where 0 = Not at all, 1 = Occasionally, 2 = A lot of the time, 3 = Most of the time). Given the overlapping literature between migraine, sensory processing, and anxiety, we focused our analysis on the 7-item anxiety subscale (e.g., "Worrying thoughts go through my mind").

Statistical analyses

Descriptive statistics were calculated, including frequencies and means for all measures of interest. Relevant parametric assumptions were confirmed using visualisations, kurtosis and skewness values, and Levene's test for homogeneity of variances.

Two tailed, between-subjects, independent t-tests were conducted to determine whether participants with and without migraine significantly differed in their sensory sensitivity, sensory avoidance, and HADS-A scores, before these variables were entered into

mediation analyses. As described, sensory sensitivity and sensory avoidance subscales were then combined into a single variable ('subjective sensory sensitivity') for mediation analysis.

Mediation analysis is a statistical approach which seeks to clarify whether the effect of an independent variable on a dependent variable occurs via a third, mediating variable. Mediation can either be complete or partial. Complete mediation would suggest that the independent variable (in this case, subjective sensory sensitivity) has no direct effect on the dependent variable (migraine), and the entire effect occurs indirectly via the mediating variable (anxiety). Partial mediation instead indicates both a direct effect (e.g., of subjective sensory sensitivity upon migraine) and an indirect effect (e.g., of subjective sensory sensitivity upon anxiety, which in turn influences migraine). In this analysis, we will determine to what extent anxiety symptoms mediate the relationship between subjective sensory sensitivity and migraine, controlling for age and gender. Mediation analyses were conducted using model four of the PROCESS macro (Hayes, 2013) in SPSS 25.0 (IBM Corp, 2017), using bootstrapping with 5000 samples and 95% confidence intervals. Indirect effects were deemed to be significant if corresponding confidence intervals do not contain zero (Hayes, 2009).

Importantly, mediation analysis does not in itself imply causal relationships unless an experimental design which manipulates variables is used. This study was instead cross-sectional, and relationships are therefore correlational. Mediation analyses using each subscale separately also found an identical pattern of results (available in *Appendix B*).

Subsequent exploratory analyses used between subjects t-tests to ascertain whether those with migraine significantly differed in their scores on the six modality subscales derived from the AASP. Bivariate Pearson correlations were also calculated, to determine the degree of collinearity between the subscales. The predictive ability of each modality upon migraine was determined individually using logistic regression, before all six were entered into a multiple logistic regression model to establish their unique contributions. Anxiety was also included to control for its influence. Relevant assumptions of logistic regression were assessed, and the Hosmer and Lemeshow goodness-of-fit test was calculated.

Finally, following interpretation of our initial mediation model, a post-hoc mediation analysis was conducted to determine whether depression symptoms, also measured by the HADS, mediated the relationship between subjective sensory sensitivity and migraine. Details of this analysis, which found no mediating effect of depression symptoms, is available in *Appendix B*.

Significance levels were specified as $p < .05$ for all analyses.

Results

Did people with probable migraine report higher sensitivity, avoidance, and anxiety?

Of 944 participants, 117 (12%) scored four or above in the MS-Q and were categorised as having probable migraine. Demographic details are presented in Table 1 and mean scores for both groups are presented as z-scores in Figure 1, calculated using normative scores available for the AASP and HADS (Brown, & Dunn, 2002; Crawford et al., 2001).

	Controls	Probable Migraine
N	827	117
Mean Age (SD)	48.3 (13.6)	53.6 (16.9)
No. female (%)	539 (65%)	100 (85%)

Table 1. A summary of demographic characteristics for both control and probable migraine participants.

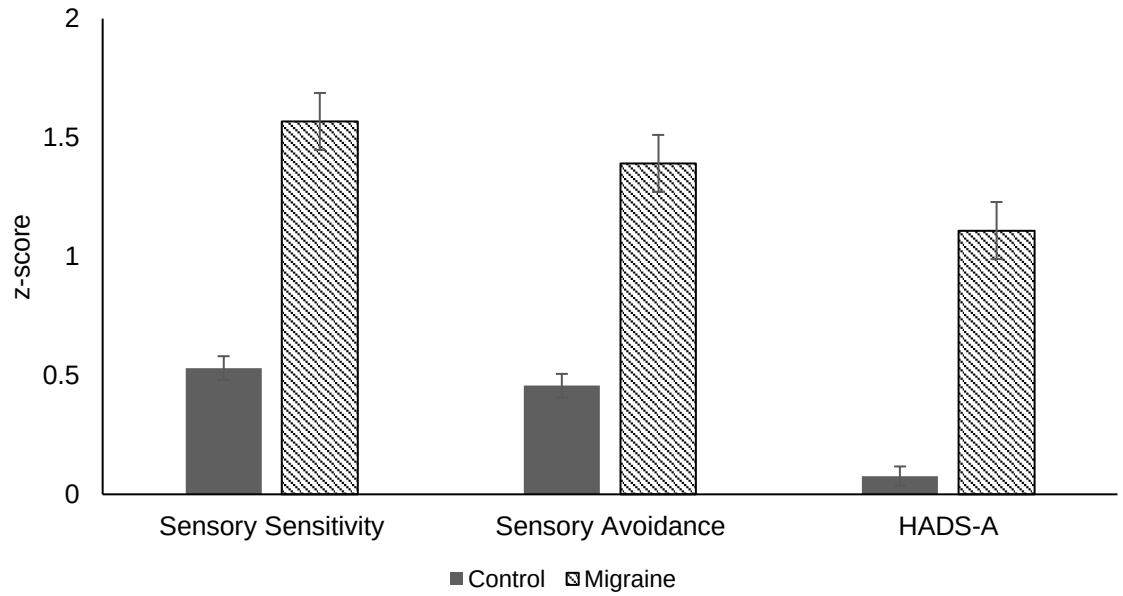


Figure 1. Mean Z-scores and their associated standard errors for migraine and control participants for AASP and HADS-A subscales calculated from available normative means (where zero indicates the expected population mean, and 1 indicates one standard deviation above this for the population). Note. AASP = Adolescent/Adult Sensory Profile, HADS-A = Hospital Anxiety and Depression Scale.

Between subjects t-tests found that mean scores significantly differed between migraine and control participants for sensory sensitivity (t (942) =8.05, p<.001, d=0.80), sensory avoidance (t (942) =7.24, p<.001, d=0.71) and HADS-A (t (942) =8.78, p<.001, d=0.87).

Does anxiety mediate the sensory association with migraine?

Mediation analysis was used to determine whether anxiety symptoms influenced the relationship between subjective sensory sensitivity and migraine (Figure 2). The total effect of subjective sensory sensitivity upon migraine was significant (c=.04, p<.001). The estimated indirect via anxiety was 0.01, and the 95% bootstrapped confidence interval was entirely above zero (0.01 to 0.02), and thus significant. The direct effect of sensory sensitivity upon migraine remained significant once this mediating effect was accounted for (c'=.02, p=.001) indicating partial mediation.

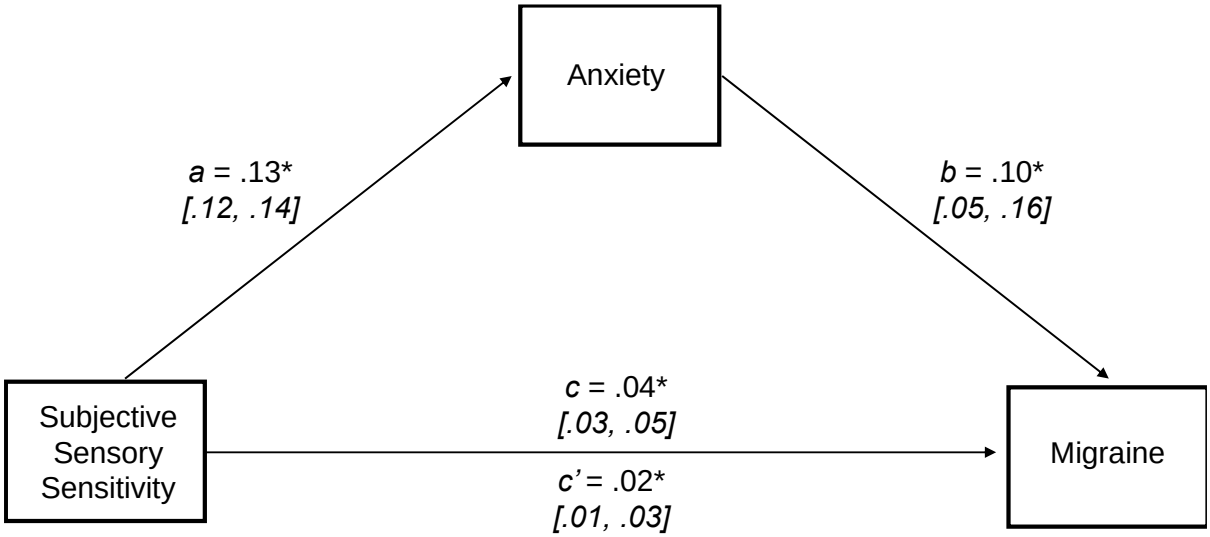


Figure 2 Mediation model of the relationship between subjective sensory sensitivity, anxiety and migraine including 95% confidence intervals for each path. Each path denotes associations between variables of interest and are on a log-odds metric. *p < .005.

Therefore, subjective sensory sensitivity was significantly associated with migraine both directly, and via the mediating effect of anxiety symptoms. Note that mediation models are correlational, and produce similar results if rotated (i.e., using subjective sensory sensitivity as the mediator). They do not establish causality.

Sensory modality analyses

These exploratory analyses sought to determine whether the association between multi-sensory processing and migraine was driven by sensitivities in particular modalities. First, it is important to note that sensitivities in the different sensory modalities are correlated with each other (see Figure 3). However, all associated variance inflation factor values were below 5 or 10, the thresholds at which collinearity between variables is a concern (Menard, 1995) (Visual = 2.81, Movement = 1.48, Touch = 2.08, Taste/Smell = 1.27, Activity = 1.86, Auditory = 2.14).

Given that each modality subscale was calculated using a different number of items (see Table 2), Figure 3 displays mean scores for each modality in a standardized form, calculated by dividing each raw mean by the number of items used to calculate that subscale.

a

	Visual	Movement	Touch	Taste/Smell	Activity
Movement	.547**	-			
Touch	.658**	.448**	-		
Taste/Smell	.388**	.312**	.421**	-	
Activity	.611**	.335**	.578**	.334**	-
Auditory	.694**	.429**	.565**	.341**	.582**

b

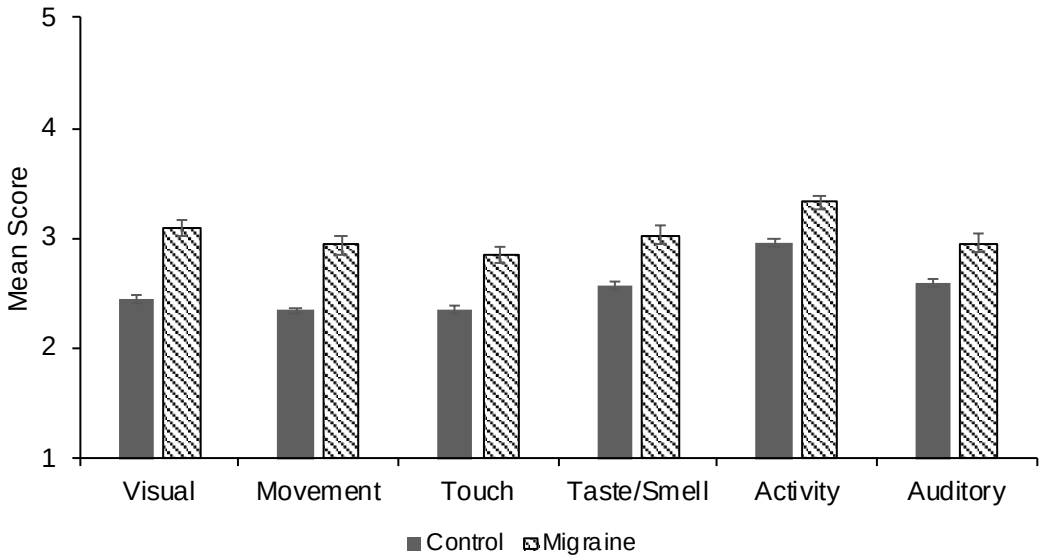


*Figure 3. a) Bivariate Pearson's correlations between each modality subscale taken from the Adolescent/Adult Sensory Profile (AASP), ** p < .01 b) Mean scores for each modality subscale for both migraine and control participants, standardized by dividing each mean by the number of items in the subscale.*

Between subjects t-tests were conducted to determine whether participants with migraine significantly differed in mean modality sensitivity scores when compared to controls. This was the case for all six modality subscales. Subsequently, individual logistic regression analyses found that each modality subscale significantly correlated with probable migraine (Figure 4).

a

Modality (no. of items)	t	Cohen's d	β	OR [95% CI]	AUC
Visual (6)	8.3**	0.82	.16	1.17 [1.13, 1.22]	0.73
Movement (4)	7.5**	0.74	.21	1.23 [1.16, 1.31]	0.69
Touch (7)	6.7**	0.66	.12	1.12 [1.08, 1.16]	0.69
Taste/Smell (3)	5.6**	0.55	.21	1.24 [1.14, 1.33]	0.65
Activity (4)	4.9**	0.49	.16	1.17 [1.10, 1.25]	0.64
Auditory (6)	4.3**	0.42	.08	1.08 [1.04, 1.12]	0.62

b

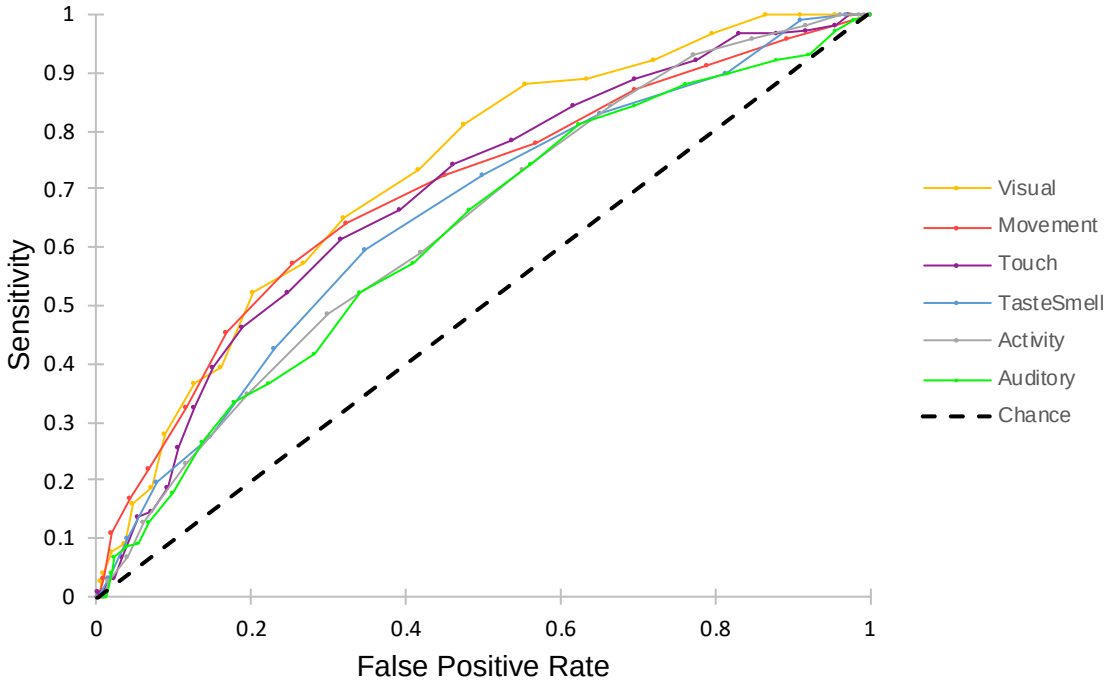


Figure 4. a) A summary of t-test and individual logistic regression analyses for modality subscales derived from the Adolescent/Adult Sensory Profile (AASP) predicting incidence of migraine, including area under the curve (AUC) values for each associated ROC displayed in Figure 5. *p < .05, **p < .01. b) Receiver Operating Characteristic (ROC) curves for each modality subscale derived from the AASP, used to predict incidence of migraine.

Receiver Operating Characteristic (ROC) curves and corresponding Area Under the Curve (AUC) values for each subscale are also displayed in Figure 4. AUC values of greater than 0.55, 0.63 and 0.71 are thought to correspond to small, medium and large effect sizes (compared with Cohen's standards; Rice & Harris, 2005). The majority of our modality subscales would thus be considered to have a corresponding medium effect size, with the exception of auditory and visual subscales, which have small and large effect sizes respectively.

To determine the relative influence of each subscale, given they correlate with each other, all six were included in a logistic regression model. The HADS-A subscale was also included to control for its influence. As can be seen in Table 2, this model produced four significant predictor subscales: movement (β=.096, p=.010), visual (β=.105, p=.004), auditory (β=-.071, p=.015) and HADS-A (β=.104, p<.001). The Hosmer and Lemeshow test was non-significant for this model (x^2 =9.398, p=.310), suggesting the model adequately fits the data.

Modality	β	OR	95% CI	p
Constant	-5.05	.01		<.001
Visual	.105	1.11	1.04, 1.19	.004
Movement	.096	1.10	1.02, 1.18	.010
Touch	.014	1.01	0.96, 1.07	.614
Taste/Smell	.078	1.08	0.99, 1.18	.090
Activity	-.018	0.98	0.90, 1.08	.697
Auditory	-.071	0.93	0.88, 0.99	.015
HADS-A	.104	1.11	1.05, 1.17	<.001

Table 2. A summary of multivariate logistic regression analyses predicting incidence of migraine, using each modality subscale and anxiety as predictor variables. *Note*. HADS-A = Hospital Anxiety and Depression Scale – Anxiety.

All analyses were repeated removing participants who reported any vestibular conditions. The pattern of results remained the same, and thus are not reported here.

Discussion

Sensitivities to sensory input are known to occur during migraine, but comparatively little is known about the extent to which such sensitivities continue between attacks. The present chapter therefore aimed to characterise whether individuals with migraine report higher interictal subjective sensory sensitivity across senses when compared to controls. In line with our hypothesis, this was found to be the case for both sensory sensitivity and sensory avoidance subscales of the AASP. We further hypothesised that this relationship would be at least partially mediated by symptoms of anxiety, given the co-occurrence and commonalities in mechanisms seen in similar populations (Breslau et al., 1991; Engel-Yeger & Dunn, 2011a; Fuller-Thomson et al., 2017; Mongini et al., 2003; Rieke & Anderson, 2018; Smith et al., 2003). This second hypothesis was also supported. Possible causes and implications of these results are now discussed.

First, the finding that increased levels of subjective sensitivity to sensory input are associated with migraine aligns with and extends initial evidence of self-reported sensory hypersensitivity in the condition (Genizi et al., 2019, 2020; Lévêque et al., 2020; Shepherd & Patterson, 2020). Previous work in adults has used questionnaires designed to assess specific sensitivities (e.g. photophobia; Lévêque et al., 2020) whereas this appears to be the first study to implement a broad, validated measure of subjective sensory sensitivity in this population. We found that these sensitivities are not limited to those inputs known to trigger migraine (e.g. light; Lévêque et al., 2020), but instead significantly higher interictal sensitivity is observed across all sensory modalities.

Second, part of the relationship between subjective sensory sensitivities and migraine is accounted for by their relationships with anxiety symptoms. This is consistent with existing evidence that finds heightened levels of anxiety in those with sensory sensitivities (Engel-Yeger & Dunn, 2011b; Rieke & Anderson, 2018).

However, as this study was cross-sectional, further research is required to explore the direction of causality. Subjective sensory sensitivity may induce anxiety as sensory input is perceived as overwhelming. Equally, input could provoke anxiety about an oncoming migraine attack in these groups, as sensory information is a cited migraine trigger (Friedman & De Ver Dye, 2009). Alternatively, increased levels of anxiety may elicit a heightened reactivity to sensory stimuli (Ayres, 1972). A causal mechanism such as this, stemming from anxiety, would be more readily amenable to treatment, particularly given that some pharmaceutical

interventions show efficacy in treating both migraine and anxiety (Srinivasan, 2019). Investigation of these relationships using a research design which allows for causal inference is needed. For example, determining whether reductions in anxiety relate to a reduction in subjective sensory sensitivity in this population could elucidate direction of effects. Importantly, information on participant's current medications was not collected in the current study, therefore the possible influence of medication upon these constructs could not be determined.

It is also important to note that although mediation effects were present, they did not entirely explain the relationship between subjective sensory sensitivity and migraine. A robust direct effect was still present, meaning even if anxiety symptoms were causative and were reduced through intervention, sensitivity might be expected to persist. The implications of interictal sensitivities therefore need to be understood and acknowledged in clinical management where necessary, with the awareness that these effects could vary across individuals. Biopsychosocial models of headache view pain and chronic illness as stemming from a complex interaction among biological, psychological and social factors, with variation in these interrelationships contributing to differing illness presentations (Andrasik et al., 2005). In the context of migraine, anxiety may be more relevant to subjective sensory sensitivity in one person than another. Future work could thus build upon these findings to determine how the presence of subjective sensory sensitivity and anxiety relate to migraine characteristics, such as frequency, severity, duration and the presence of aura (which is known to relate to sensory sensitivities; Granovsky et al., 2018; Pearl et al., 2020).

We also investigated whether sensitivities in certain sensory modalities were particularly important in predicting incidence of migraine; visual, movement and auditory subscales were significant predictors when controlling for scores in other modalities, as well as anxiety. We had speculated the visual domain may drive the main effects seen in our analyses, given visual triggers and auras are commonly reported (Friedman & De Ver Dye, 2009; Russel & Olesen, 1996).

However, it is noteworthy that movement sensitivities were also significantly and positively predictive of migraine in these analyses. The movement subscale of the AASP assesses the presence of dizziness and avoidance or dislike of movement, known to be relatively common in those with migraine (Benatto et al., 2019; Powell et al., 2020a). The association between movement sensitivity and migraine highlights how understanding

sensory experiences in the condition could be beneficial in improving the current unmet need for non-pharmaceutical intervention. Physical activity is reported to reduce the severity of migraine, and yet those with migraine are found to exercise less regularly (Amin et al., 2018). Individuals with migraine may therefore need additional support to engage with exercise, with a focus upon improving these sensitivities. Exercise may not only improve migraine, but additionally feelings of anxiety (Asmundson et al., 2013) which independently, and via the influence upon sensory sensitivities reported here, could further improve upon wellbeing.

In contrast to the effects of the visual and movement subscales, the auditory subscale was significantly predictive of migraine but with a negative coefficient. This implies a higher subjective auditory sensitivity is associated with reduced odds of migraine, which is counterintuitive in the context of auditory sensitivities and triggers (Friedman & De Ver Dye, 2009). It is possible that this unexpected finding is merely statistical in nature, which can happen in a regression model where a notable amount of shared variance between factors exists, as is the case here. Additional work would be needed to determine the nature and role of subjective auditory sensitivity in migraine.

Lastly, for heightened sensitivity to touch and smell/taste, our results do not rule out their relevance for predicting migraine, but these contributions could not be disentangled from the correlations of these senses with vision, movement, hearing, and anxiety. Though widely used and validated, one limitation of the AASP is the limited number of items used to reflect taste and smell; of 30 questions assessing subjective sensory sensitivity, only three relate to taste/smell, and ultimately only one assesses olfactory sensitivity. Given this lack of clarity on the role of sensitivities in these modalities, and the prominence of olfaction in migraine trigger literature (Borini et al., 2011; Friedman & De Ver Dye, 2009), future study could use initial findings reported here to more extensively explore subjective sensitivity in each modality independently using a measure with established modality subscales.

Enhancing understanding of modality specific sensitivities will also benefit from study which moves beyond focusing on only one form of sensory sensitivity, as the current literature tends to. For example, a combined approach that considers not only subjective sensory sensitivity but additionally sensitivity at a behavioural and neural level. It is not clear whether subjective sensory sensitivity and behavioural sensitivity are distinct; work relating the AASP to experimental sensory testing is largely focused on conditions such as autism, and results are mixed (Jones et al., 2009; Minshew & Hobson, 2008). Recent work considering these

relationships in the general population also finds that detection thresholds are not related to self-reported sensitivity in either visual or auditory domains (Schulz & Stevenson, 2021), and instead argue they are distinct constructs. It is thus not known whether behavioural and subjective sensitivity would consistently co-occur in the same individuals with migraine. Further, combining questionnaire measures with neurophysiological data would allow us to relate subjective sensory sensitivities to existing models of cortical excitability (Ambrosini et al., 2003; Antal et al., 2005; Shepherd, 2001) to determine what underlies subjective sensory sensitivity at a neural level in this group.

Additional study limitations include the nature of recruitment; participants volunteered themselves after receiving an emailed advert, which potentially introduces self-selection bias. Despite emphasising the inclusivity of the survey in our recruitment advert in an attempt to mitigate this bias, this could explain why, for sensory sensitivity measures, our control participants scored slightly above normative data.

Participants were also not asked to confirm whether they were currently experiencing a migraine attack. However, the AASP does not ask about sensitivity in the current moment, but instead participants report the frequency with which each item is experienced. It is assumed this would therefore represent the everyday, interictal experience. Additionally, it could be argued that individuals with migraine are unlikely to undertake a lengthy computer survey (as was required in the study) during an attack as this could exacerbate symptoms (Shepherd, 2010) and there was no time limit to complete the survey.

Finally, as this was not an exhaustive exploration of possible correlates or mediators of sensory experiences in migraine, there are other factors which may also be relevant to relationships found here. For example, although anxiety has more established associations with sensory hypersensitivity, other traits, conditions or clinical symptoms comorbid with migraine (e.g., neuroticism; Breslau & Andreski, 1995) may also be relevant. How these parameters might affect the relationships described here would be an interesting avenue for future work, for which this study can provide initial insight.

Summary

In summary, interictal subjective sensory sensitivities were found to be significantly increased in migraine. This finding expands on extant literature by using validated questionnaire measures to consider sensitivities across several sensory modalities, and

additionally using a large community sample. We found that the relationship between subjective sensory sensitivity and migraine was partially mediated by anxiety symptoms. Although the causal mechanisms of this mediation are yet to be determined, this finding highlights the relevance of affect in sensory sensitivities between attacks. Targeting these symptoms therapeutically could improve upon sensory experiences which may be affecting quality of life and access to intervention in this population. Finally, it was found that visual and movement sensory sensitivities positively predicted incidence of migraine, highlighting how these senses may be particularly important to the experience of sensory sensitivity in the disorder. Further investigation is needed to better understand the specific relevance of these modalities, perhaps with a focus upon creating a unified understanding of sensory sensitivity across subjective, behavioural, and neural measures in migraine and beyond.

Chapter 3: Cross-condition differences in subjective sensory sensitivity: modality specific patterns, and the role of comorbid diagnoses

Introduction

As discussed in the General Introduction, subjective sensory sensitivity refers to first person reports of experiencing sensory stimuli as aversive, distracting or overwhelming (Ward, 2018). Examples of stimuli which might be problematic span sensory modalities and may include input such as bright lighting, loud noises, light touch and fast-paced sports (Brown & Dunn, 2002). Importantly, as highlighted in Chapter 2, subjective sensory sensitivity is distinct from (but conceptually related to) behavioural sensory sensitivity, relating to differences in detection or discrimination of sensory input, and neural sensitivity, which refers to the degree of neural activation in response to this input (Ward, 2018). Sensitivity can vary naturally in the general population (Robertson & Simmons, 2013), and reports of increased subjective sensory sensitivity are consistently reported across a range of mental, neurological and neurodevelopmental conditions.

For some such diagnoses, differences in sensory sensitivity appear more central than others. For example, hyper or hypo reactivity to sensory input forms part of the diagnostic criteria for autism (American Psychiatric Association (APA), 2022), with evidence finding sensory differences in over 90% of autistic individuals, persisting across age and IQ ranges (Leekam et al., 2007). Similarly, the diagnostic criteria for migraine (ICHD-3, 2013) specifies sensitivity to light and sound during an attack as a headache characteristic, with similar sensory inputs known to trigger a migraine attack (Friedman & De Ver Dye, 2009). However, increased sensitivities are also reported in many other conditions, including: obsessive-compulsive disorder (OCD; Rieke & Anderson, 2018), post-traumatic stress disorder (PTSD; Engel-Yeger et al., 2013), attention deficit hyperactivity disorder (ADHD; Lane & Reynolds, 2019), schizophrenia (Brown et al., 2002), anorexia nervosa (AN; Zucker et al., 2013), bulimia (Bell et al., 2017), generalized anxiety disorder (Khodabakhsh et al., 2020), depression (Khodabakhsh et al., 2020), chronic tic disorders (Isaacs et al., 2022), and persistent postural perceptual dizziness (Powell et al., 2020b). Subjective sensory sensitivity therefore appears to be a transdiagnostic symptom, appearing across diagnostic categories.

Research thus far has often focused on these conditions or areas of neurodiversity in isolation, detailing how their sensory experiences differ from individuals without the same

diagnosis. Fewer studies have considered similarities and differences across conditions, and the well-known role of sensory differences in autism means that research often use this diagnosis as a point of comparison. For example, recent work reports that sensory sensitivities are comparable across children with ADHD and autism (Dellapiazza et al., 2021). Other conditions, including eating disorders (Dovey, Kumari, & Blissett, 2019) and synaesthesia (Ward et al., 2017), are found to show similar patterns of sensory sensitivities to those with autism, highlighting these experiences as a shared feature. Comparison beyond autism is limited, and contrasting methodologies in extant literature (e.g., differences in measures, samples) makes cross study comparison challenging. It is therefore of interest to consider how sensitivity might differ across clinical conditions, in terms of magnitude and patterns of sensory modalities, within the same investigation.

Additionally, there is a need to consider the role of comorbidities. It is known that for many clinical diagnoses, the condition rarely exists in isolation and co-occurring diagnoses are common (Kessler et al., 2005; Krueger & Eaton, 2015). For example, disorders of anxiety commonly co-occur with each other (Spinhoven et al., 2014), with other mood disorders (Spinhoven et al., 2014), as well as eating (Swinbourne & Touyz, 2007), neurological (Smitherman et al., 2013) and perceptual disorders (Carmichael et al., 2019). Comorbidities can also be substantial. For example, comorbidity of PTSD with depression has been reported to be as high as 84% (Spinhoven et al., 2014). Importantly, comorbid conditions show evidence of both mediating and moderating effects on sensory sensitivity. For example, migraine commonly co-occurs with anxiety at both trait and diagnosis level (Lantéri-Minet et al., 2005; Mongini et al., 2003), and the association between subjective sensitivity and migraine was found in Chapter 2 to be partially mediated by anxiety symptoms. Similarly, Zengin and Huri (2022) report significant differences in sensory sensitivity across those with schizophrenia with and without co-occurring substance use disorders. Considering subjective sensory sensitivities in the absence of key comorbidities may therefore impede our understanding of causes of sensitivity, and identification of who may be most affected.

Improving our understanding of these sensitivities, how they compare across conditions and how they might impact an individual, has clinical importance. Within clinical populations, differences in sensory experience positively correlate with the severity of core phenotypic symptoms such as compulsions in children with OCD (Lewin et al., 2015), autistic traits (Tavassoli et al., 2012), ADHD traits (Panagiotidi et al., 2018), and depression and

hypomania in those with affective disorders (Engel-Yeger et al., 2018). Sensory sensitivities also play a negative modulating role in health and quality of life (Costa-lópez et al., 2021). Prospective studies have found early indicators of sensory sensitivity to be predictive of later anxiety symptoms, potentially acting as a risk factor for anxiety disorders (Carpenter et al., 2019).

Therefore, based on existing work which finds subjective sensory sensitivity to be a common transdiagnostic symptom, and the potential clinical importance of enhancing our understanding of sensitivities, this study sought to compare the nature of subjective sensory sensitivity across clinical conditions, whilst considering the potential role of comorbid diagnoses. This approach aligns with emerging models and recommendations which propose the need to consider transdiagnostic dimensions to clinical disorders (E.g., Hierarchical Taxonomy of Psychopathology; Kotov et al., 2017; Research Domain Criteria Initiative; Insel et al., 2010), as a result of significant genetic and phenotypic overlap across conditions (Hettema et al., 2005; Thornton et al., 2016). We also considered the potential role of cumulative diagnoses, given high levels of comorbidity (Kessler et al., 2005), with a view to providing clinically relevant estimations of how subjective sensitivities may increase with increasing diagnoses. The research questions were therefore:

1. How do patterns of modality specific sensory sensitivities compare across clinical diagnoses?
2. Is heightened sensory sensitivity consistently found across clinical conditions, when compared to individual who report no diagnoses?
3. Do these conditions continue to be associated with measures of subjective sensory sensitivity when controlling for co-occurring conditions, age, and gender?

Participants were recruited through the university and via social media forums and were asked to complete two commonly used questionnaire measures of subjective sensory sensitivity: the Adolescent/Adult Sensory Profile (Brown & Dunn, 2002) and the Glasgow Sensory Questionnaire (Robertson & Simmons, 2013). Participants also self-reported diagnosis or self-identification with clinical conditions. Analyses focused only on diagnoses for which we had sufficient power: ADHD, anorexia, autism, anxiety, bulimia, depression, migraine, OCD, PTSD, and synaesthesia.

Methods

Participants

Participants were recruited via two methods. The first involved undergraduate students at Cardiff University, who completed the online survey in exchange for course credit; of 591 participants, 466 provided complete data for all measures. The second recruitment method involved posting the survey link on various support and information forums on social media (Facebook, Reddit, Twitter). Forums were found by searching the condition name (e.g., "ADHD") and selecting associated groups or pages. Prior to distribution, the study's aims were clearly explained, and approval to post was sought from forum administrators or moderators. 174 responses were received, 112 of which had complete data. These participants were not compensated for participation.

Demographic information for both samples is displayed in Figure 1. The final sample (n = 578) had a mean age of 22.2 (SD = 8.5) with 11.6% identifying as male, 82.5% female, 5.5% as other and .3% responding 'prefer not to say'. The most frequent gender identities among those self-reporting as 'Other' included: gender queer, gender fluid, non-binary and agender. For clarity, these individuals will subsequently be referred to using the umbrella term gender non-binary.

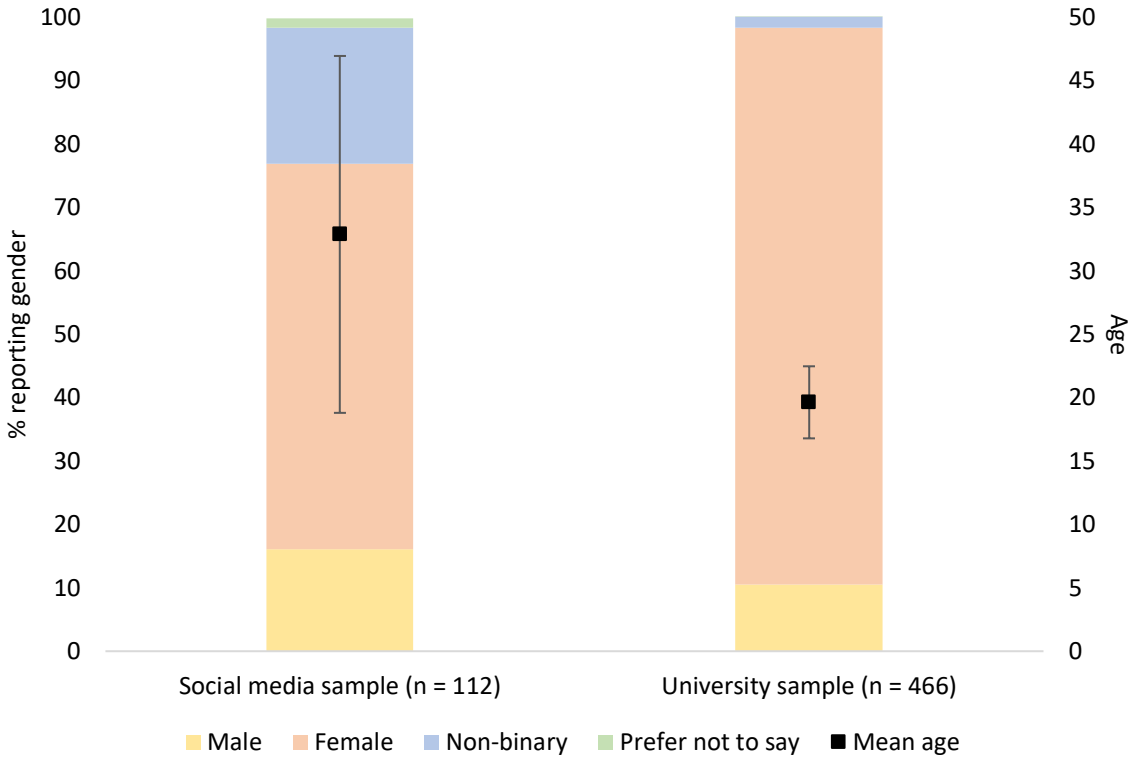


Figure 1. Demographic details (age, gender) for both social media and university samples.

Materials

All questionnaires were delivered online via Qualtrics survey. Demographic information was collected (age, self-reported gender), along with self-reported diagnosis of or identification with listed clinical conditions, chosen as they have shown previous association with subjective sensory sensitivities. Space was also provided to indicate conditions not pre-specified. Details of reported diagnoses are provided in *Appendix A*.

It was decided *a priori* that only clinical conditions with n > 23 would be included in further analyses, to allow adequate power. Ten clinical conditions were reported by over 20 individuals, namely: ADHD, anorexia, anxiety, autism, bulimia, depression, migraine, OCD, PTSD, and synaesthesia. Subsequent analyses therefore centre on these diagnoses. A count variable was also calculated, which summed the total number of clinical conditions that were reported for each participant.

Adult/Adolescent Sensory Profile (AASP; Brown, & Dunn, 2002)

The AASP is a 60-item self-report measure of sensory function as it relates to Dunn's model (Dunn, 1997). Respondents are asked to indicate the frequency with which they perform a given behaviour using a 5-point Likert scale, which extends from "Almost Never" (1) to "Almost Always" (5). An equal number of items are summed to compute four quadrant scores which can be used to characterize sensory experience. Given we were interested in sensory sensitivities specifically, we focused on only two of these. Namely: sensory sensitivity (dislike for sensory stimuli and distractibility: e.g., "I'm uncomfortable wearing certain fabrics"), and sensory avoidance (behaviours which limit exposure to stimuli and restrict unpredictability: e.g., "I avoid or wear gloves during activities that will make my hands messy"). Higher subscale scores indicate greater levels of the corresponding sensory behaviour. The AASP quadrants have been found to have moderate to good internal consistency (Cronbach's α between 0.66 and 0.81) and construct validity (Brown & Dunn, 2002; Brown et al., 2001).

Items of the AASP assess sensory experience across six modalities. However, when calculating total modality scores, items are unbalanced (e.g., three items sum to create a taste/smell subscale, whereas six sum for the visual subscale). For this reason, modality-specific sensitivities were assessed using the Glasgow Sensory Questionnaire, as items are equally distributed across sensory modalities.

Glasgow Sensory Questionnaire (GSQ; Robertson & Simmons, 2013)

The GSQ is a 42-item measure of sensory function. Participants respond on a 5-point Likert scale from "Never" (0) to "Always" (4) to items relating to sensory experience and/or behaviours. Seven sensory modalities (visual, auditory, olfactory, tactile, gustatory, vestibular, and proprioceptive) are assessed using 6 questions each (three assessing hyper-sensitivity, three assessing hypo sensitivity). Scores can subsequently be summed to create total hypo and hypersensitivity scores, and additionally hyper and hypo sensitivity totals for each modality. In these analyses, only modality hypersensitivity totals were used.

Example sensitivity items include "Do you cut labels out of your clothes?" and "Do bright lights ever hurt your eyes/cause a headache?". It should be noted that the GSQ has been designed to detect sensory differences that are more prevalent in autism, however it is not limited to use in autistic individuals (Robertson & Simmons, 2013).

Statistical Analyses

All analyses were completed using SPSS Statistics 26 (IBM Corp, 2017) and RStudio (R. Core Team, 2022). Descriptive analyses considered cross-condition differences in affected sensory modalities. Mean z-scores for each sensory modality of the GSQ were derived for each condition, standardized against the scores from participants in our sample reporting no clinical diagnoses (n = 243).

Welch's t-test was used to determine whether individuals with each clinical condition significantly differed from individuals reporting no clinical condition, consistent with existing literature. Data met assumptions of normality, however due to the possible effect of unequal sample sizes (condition versus no condition) upon conclusions of the student's t-test (Delacre et al., 2017), Welch's t-test was chosen. Bonferroni correction was applied (20 statistical tests), resulting in a significance threshold of $p < .003$.

The forced entry regression method was then used to conduct four multiple linear regressions. Assumptions of normality, linearity and homoscedasticity were assessed using visual inspection of residual plots, and collinearity was evaluated using variance inflation factor and tolerance values. To allow for meaningful interpretation of unstandardized coefficients across independent variables, the dependent variables (AASP subscales of sensory sensitivity and sensory avoidance) were log-transformed prior to analysis (Benoit,

2011). As a result, unstandardized coefficients can be interpreted as the approximate percent change in sensory sensitivity subscales when a given diagnosis is reported.

For each subscale, one regression model was calculated which included all clinical conditions as predictor variables, along with age and gender (gender coded as dummy variables). A second, separate regression model included age, gender, and total number of reported diagnoses as predictor variables, to determine how the number of reported clinical conditions associates with sensory differences. Two participants who did not provide their gender were excluded from this analysis. Phi coefficients were also calculated to assess and display the association between co-occurring diagnoses.

Results

Descriptive analyses: cross-modality comparison

Figure 2 displays z-scores for each sensory modality of the GSQ, separated by reported clinical condition. Those reporting autism, PTSD and synaesthesia show the greatest magnitude of multi-modal sensory sensitivities, with many z-scores being greater than 1. Despite similar magnitudes, the pattern of sensitivities differed across these conditions; for example, although high auditory sensitivity was common to all three conditions, those reporting autism showed a high degree of tactile and proprioceptive sensitivity that was not seen to the same extent in individuals reporting synaesthesia and was reduced in those with PTSD.

Other more condition-specific patterns are evident in those reporting a diagnosis of migraine or bulimia. Auditory, visual, and olfactory sensitivity was evident in migraine, aligning with sensory input known to trigger an attack (Friedman & De Ver Dye, 2009). Those reporting bulimia instead show a pattern characterised by increased proprioceptive, auditory, olfactory, and tactile sensitivity, with gustatory sensitivity being more similar to that of those reporting no clinical conditions.

Comparatively similar patterns of sensitivity can be seen across anorexia, anxiety, depression, and to some extent ADHD and OCD (although there is indication of specific visual sensitivities). Sensory modalities tended to be similarly affected, although varied in scale across these conditions. For example, similar cross-modality patterns are seen in anxiety and depression, however depression with greater magnitude.


ADHD (n = 74)
Anorexia (n = 37)
Anxiety (n = 232)
Autism (n = 56)
Bulimia (n = 27)
Depression (n = 157)
2.0
1.5
1.0
0.5
0.0
Modality
Visual
Auditory
Gustatory
Olfactory
Tactile
Vestibular
Proprioceptive

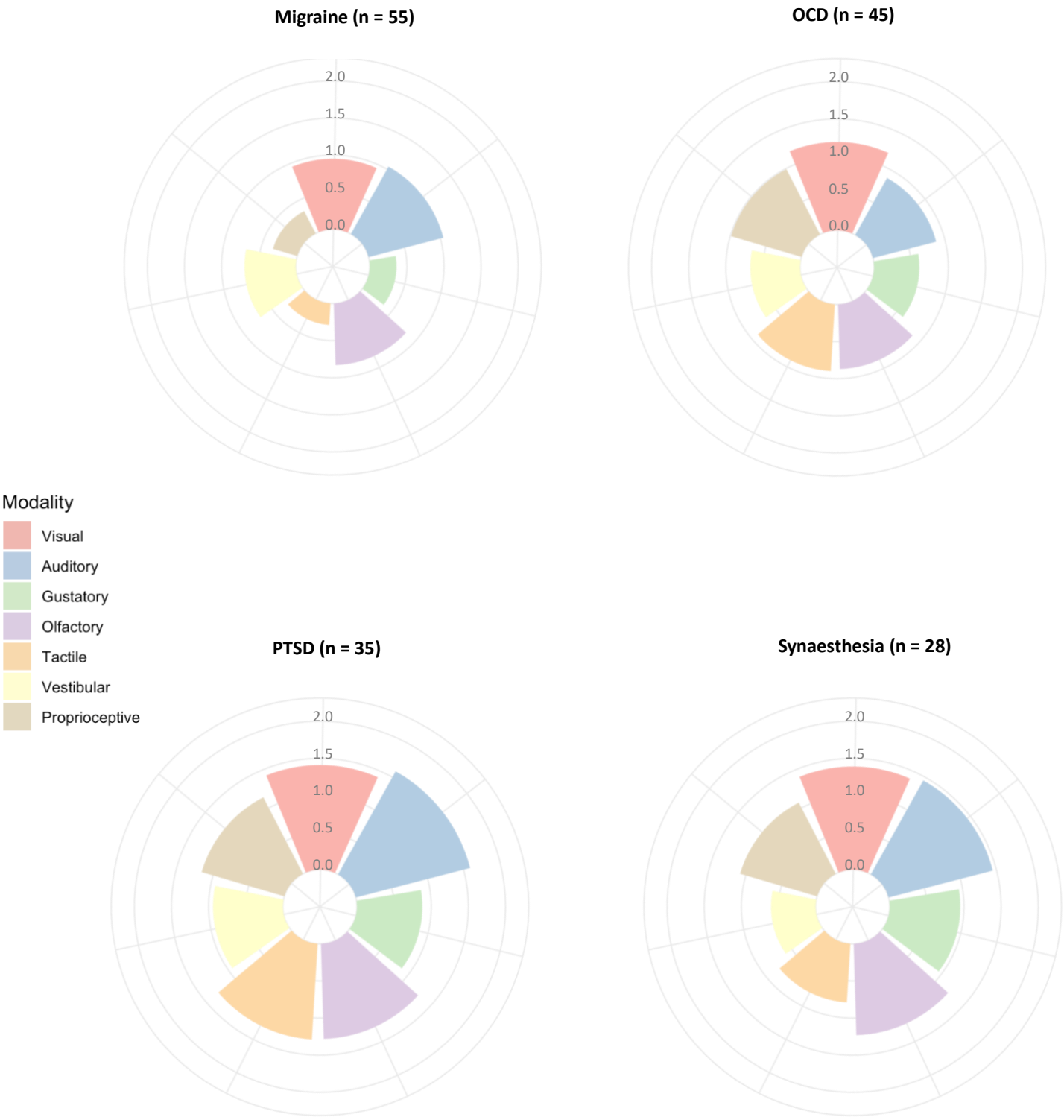


Figure 2. Radar charts displaying the mean z-scores for modality subscales of the Glasgow Sensory Questionnaire according to reported clinical diagnoses. Z-scores calculated against participants reporting no clinical diagnoses. *Note ADHD = attention deficit hyperactivity disorder; OCD = obsessive compulsive disorder; PTSD = post-traumatic stress disorder.*

Is each clinical condition associated with differences in subjective sensory experience?

	Sensory Sensitivity		*Sensory Avoidance*	
Diagnosis	*Mean*	*Welch statistic (df)*	*Mean*	*Welch statistic (df)*
ADHD	50.0	-7.4 (98.5)	49.9	-8.0 (90.8)
Anorexia	49.2	-5.2 (44.8)	46.6	-3.9 (42.5)
Anxiety	46.2	-6.4 (477.8)	44.1	-6.1 (446.1)
Autism	52.0	-7.0 (63.7)	55.0	-11.9 (66.2)
Bulimia	50.4	-4.2 (28.6)	47.1	-3.3 (28.7)
Depression	47.9	-7.6 (265.8)	46.9	-8.3 (230.2)
Migraine	46.3	-2.6 (65.9)	47.0	-3.8 (60.9)
OCD	49.3	-4.5 (51.0)	47.2	-3.84 (49.6)
PTSD	51.8	-5.4 (37.7)	52.9	-6.16 (36.8)
Synaesthesia	48.0	-2.5 (29.1)	52.2	-6.24 (29.8)
None	39.7		36.3	

Table 1. A summary of mean scores on sensory sensitivity and sensory avoidance subscales of the AASP, and associated Welch statistics, according to clinical diagnosis. *Note ADHD = attention deficit hyperactivity disorder; OCD = obsessive compulsive disorder; PTSD = post-traumatic stress disorder.*

To determine whether sensory sensitivity scores were significantly higher in those reporting the clinical conditions of interest, a series of Welch's t-tests were conducted. Across clinical conditions, significantly higher scores were found in the AASP subscales of sensory sensitivity and sensory avoidance when those reporting the clinical condition were compared to those who reported none (See Table 1, all $p < .001$). This supports condition specific increases in subjective sensory sensitivity, across both subscales used.

The effect of comorbid conditions

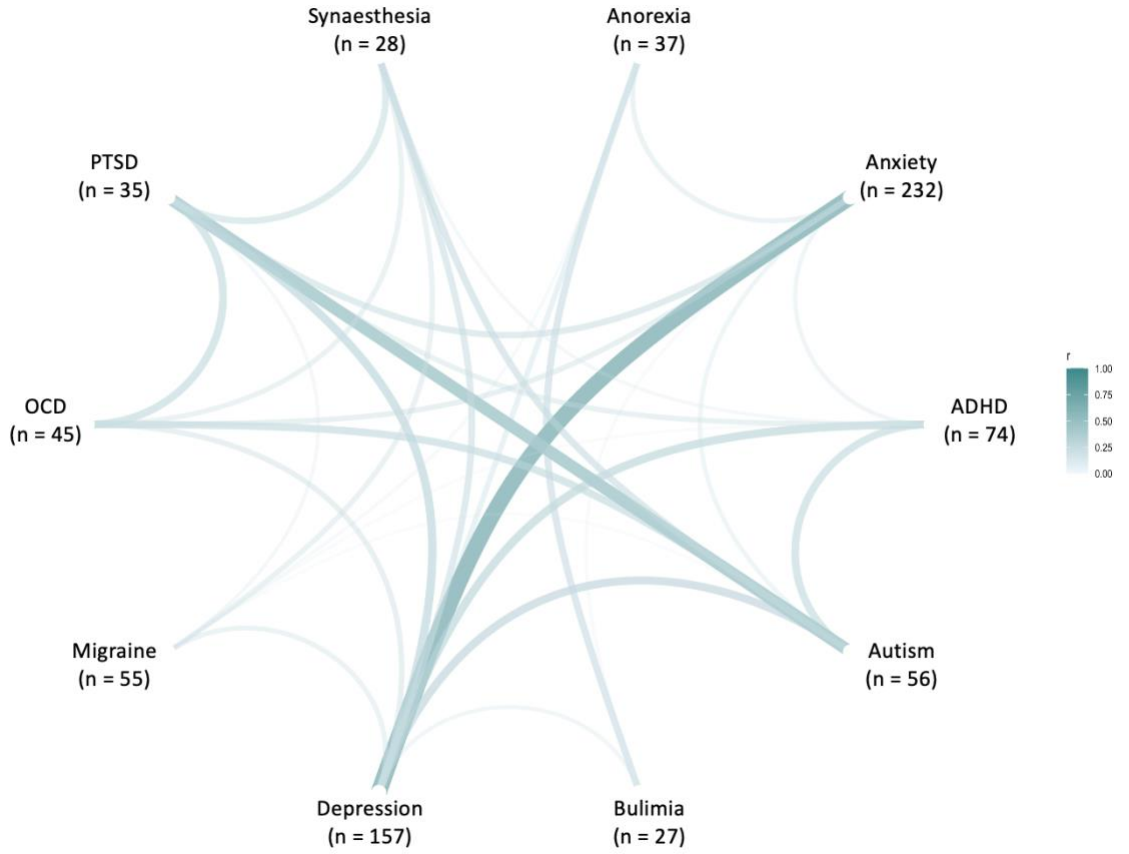


Figure 3. Graphical representation of comorbid diagnoses within the sample (n = 335), calculated based upon phi coefficient between each self-reported diagnosis or area of neurodiversity. Only coefficients > .10 are displayed. *Note ADHD = attention deficit hyperactivity disorder; OCD = obsessive compulsive disorder; PTSD = post-traumatic stress disorder.*

Figure 3 displays the patterns of comorbidity across diagnoses using in the current analyses. To determine the unique association of each clinical condition with differences in the sensory subscales of the AASP, all clinical conditions were entered as predictor variables into two separate regression models for sensory sensitivity and for sensory avoidance, with age and gender also included to control for their influence.

In the regression analysis predicting the sensory sensitivity subscale (Figure 4), reported diagnoses of ADHD, anxiety, autism, bulimia, and depression were significant predictors ($p < .05$) whilst anorexia, migraine, OCD, PTSD, synaesthesia, and age were not. Identifying as female was associated with significant higher sensory sensitivity scores when compared to identifying as male or gender non-binary. The overall model was also significant: F (13, 564) = 11.39, $p < .001$, with Adjusted $R^2 = .21$. In the regression analysis where sensory

avoidance was instead entered as the dependent variable (Figure 5), significant associations were found between ADHD, anxiety, autism, depression, synaesthesia, and age. Non-significant associations were found with anorexia, bulimia, migraine, OCD, PTSD, and gender. The overall model was significant: F (13, 564) = 19.08, p < .001, with Adjusted R^2 = .31.

Subsequent regression aimed to investigate the role of increasing diagnoses upon reports of subjective sensory sensitivity. Number of reported conditions, age, and gender were therefore included as predictors in two regression models predicting sensory sensitivity and sensory avoidance.

The sensory sensitivity model was significant, F (4, 573) = 30.465, p < .001 with Adjusted R^2 = .17. Number of reported diagnoses (b = .065, p < .001) was found to be a significant predictor, as was identifying as female (b = .086, p = < .001) or a non-binary gender identity (b = .099, p = .034). Age was not significantly associated with sensory sensitivity scores in this model (b = -.001, p = .551). These findings suggest that additional diagnoses are associated with an approximately 7% change in scores on the sensory sensitivity subscale.

The sensory avoidance model was also significant overall, F (4, 573) = 47.43, p < .001, with Adjusted R^2 = .25. Number of diagnoses significantly associated with sensory avoidance (b = 0.08, p < .001), as did age (b = .003, p = .016). Gender did not (female: b = 0.2, p = .496; non-binary gender: b = .06, p = .260). This suggests that with each additional reported diagnosis, there is expected to be an approximately 8% change in sensory avoidance scores.

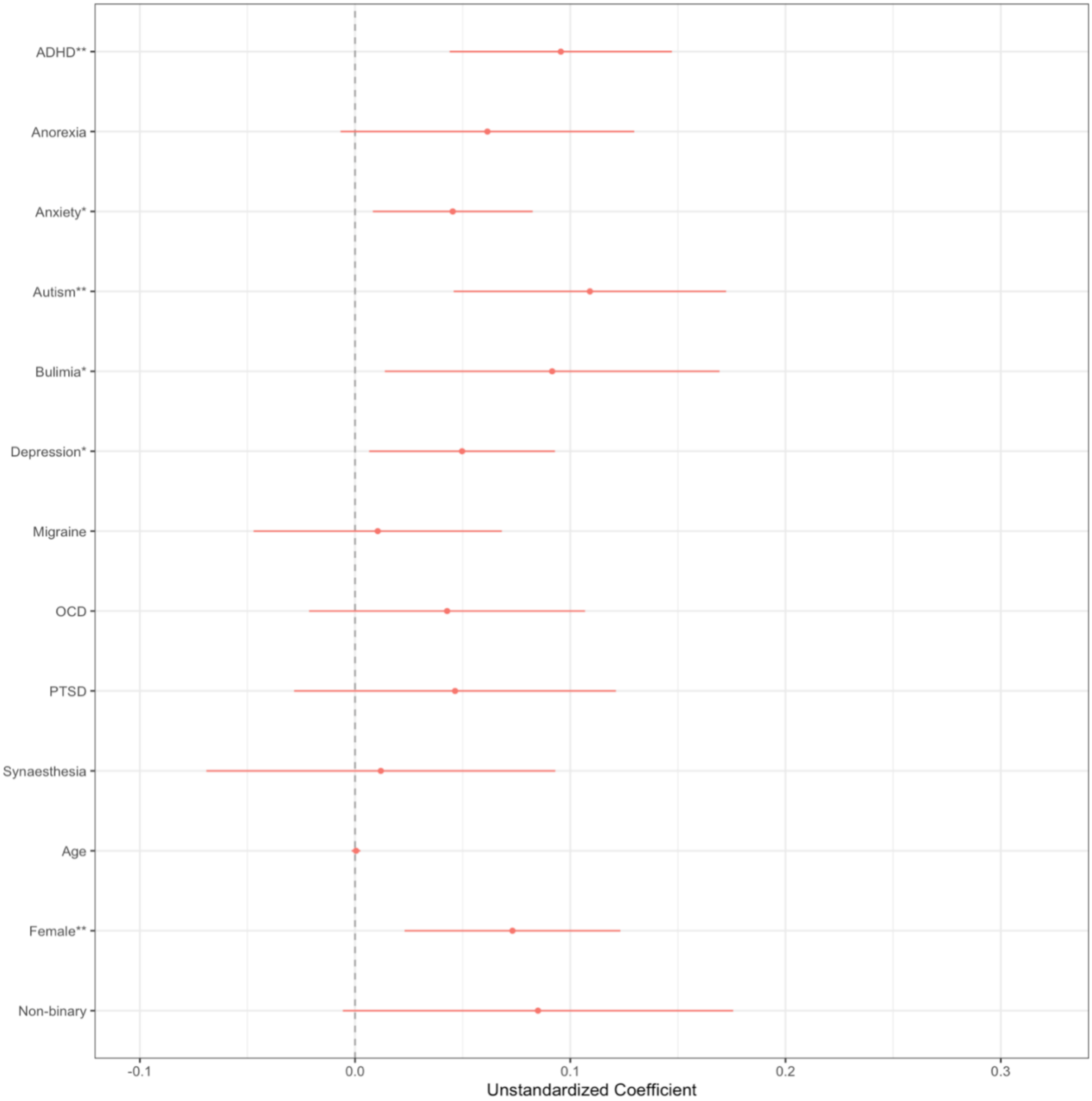


Figure 4. Unstandardized coefficients (and corresponding 95% confidence intervals) derived from regression analysis assessing the association between reported clinical conditions, age, and gender with the sensory sensitivity subscale of the Adolescent/Adult Sensory Profile (AASP). Due to the log-transformed dependent variable, unstandardized coefficients can be interpreted as approximate percentage change in sensory sensitivity when a given diagnosis is reported. *Note ADHD = attention deficit hyperactivity disorder; OCD = obsessive compulsive disorder; PTSD = post-traumatic stress disorder.* $*p < .05$ $**p < .01$

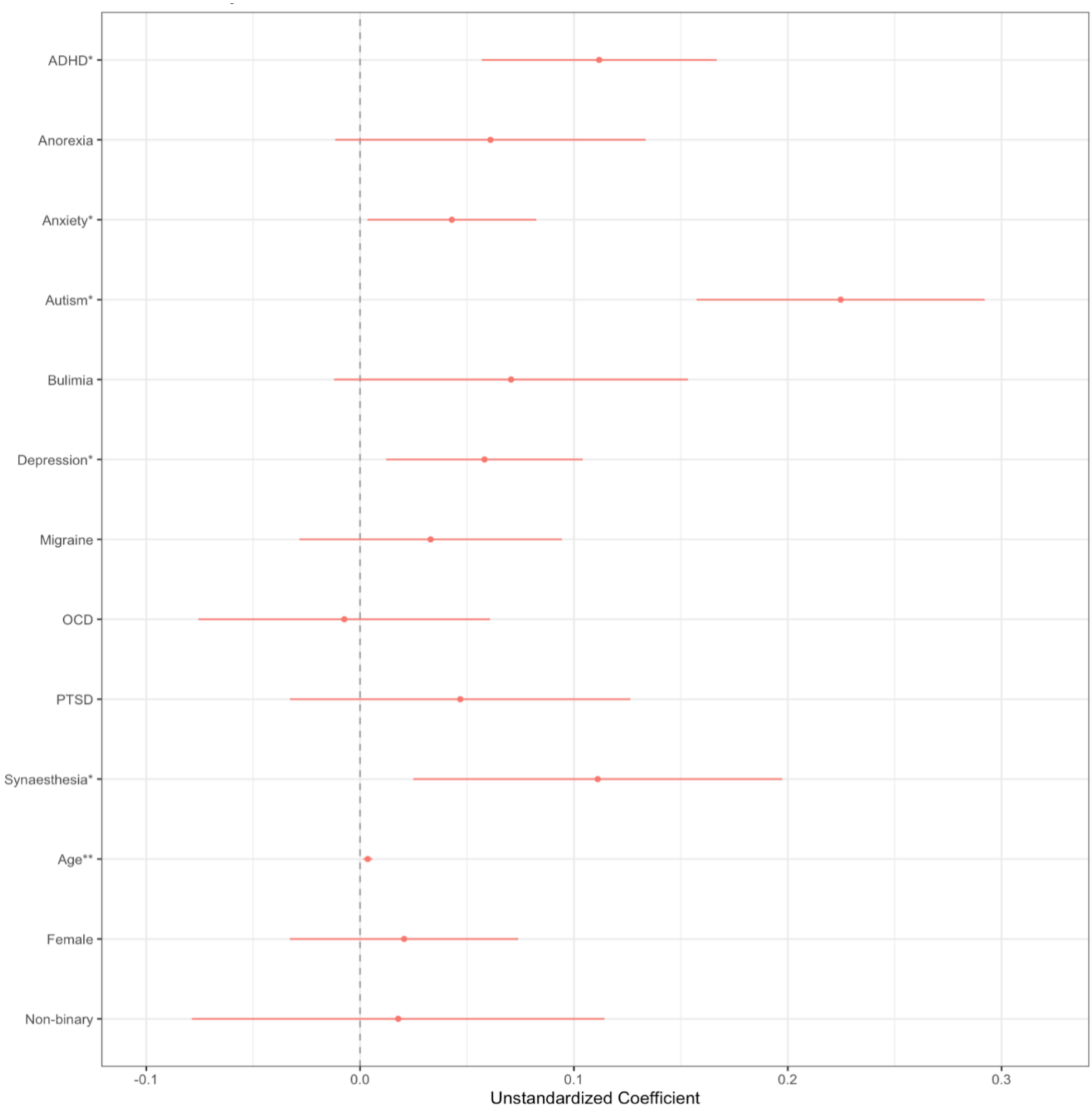


Figure 5. Unstandardized coefficients (and corresponding 95% confidence intervals) derived from regression analysis assessing the association between reported clinical conditions, age, and gender with the sensory avoidance subscale of the Adolescent/Adult Sensory Profile (AASP). Due to the log-transformed dependent variable, unstandardized coefficients can be interpreted as approximate percentage change in sensory sensitivity when a given diagnosis is reported. *Note ADHD = attention deficit hyperactivity disorder; OCD = obsessive compulsive disorder; PTSD = post-traumatic stress disorder.* $*p < .05$ $**p < .01$

Discussion

The present study investigated the subjective sensory sensitivities reported across several clinical diagnoses and areas of neurodiversity. Descriptive analyses suggested that whilst some diagnoses may show similar patterns of affected modalities which differ in magnitude (e.g., anxiety, depression), other conditions showed more condition-specific sensitivities (e.g., migraine, bulimia). When compared to individuals reporting no diagnoses, all ten clinical diagnoses were associated with significantly higher subjective sensory sensitivity. However, subsequent regression analyses assessed the unique association of each reported condition with sensory sensitivity, controlling for co-occurrence of other diagnoses. Conditions including ADHD, anxiety, autism, depression, bulimia, and synaesthesia were significantly associated with sensory variables, suggesting these conditions uniquely contribute to sensory experiences, and differences found in other conditions may be explained by comorbidity. Age was also associated with enhanced sensory avoidance, as has been found previously (Brown & Dunn, 2002), and significantly increased sensory sensitivity was associated with identifying as female or non-binary, when compared to identifying as male. Finally, an association between number of reported diagnoses and subjective sensory sensitivities was found, suggesting a role for additive effects on sensory experiences.

Modality-specific sensitivities

Modality-specific sensitivities were compared across groups of individuals who reported a diagnosis of each condition. Autism, PTSD, ADHD, and synaesthesia emerged as conditions which differed most in magnitude from individuals who did not report any diagnoses. Given that the GSQ aims to pick up on sensory behaviours more prevalent in autism, this suggests that those with PTSD and synaesthesia may experience similar sensitivities to individuals on the autism spectrum. This has previously been suggested in synaesthesia (Ward et al., 2017), but appears to be a novel finding for PTSD.

Conditions such as anorexia, anxiety and depression appeared to show a similar pattern of sensitivities, with broadly similar cross modality effects. Modality specific sensitivities were also comparable in bulimia, with the exception of reduced gustatory sensitivity. OCD appeared to show specifically heightened visual sensitivity in particular, although differences were also present in other modalities including olfactory, auditory, tactile, and proprioceptive. These patterns of modality specific sensitivities may be useful in

clinical practice, in terms of providing insight into sensory inputs which may be more challenging for some individuals reporting a given diagnosis.

In subsequent analyses, all ten clinical conditions were found to have significantly increased overall subjective sensory sensitivity as measured by the AASP. This supports existing literature, replicating increased sensitivity in conditions with strong evidence base (Crane et al., 2009; Engel-Yeger & Dunn, 2011b), and bolstering where evidence is more limited (Lane & Reynolds, 2019; Price et al., 2021; Rieke & Anderson, 2018). It should be noted that these clinical groups were not separated in terms of comorbidities; that is, individuals did not exclusively report one diagnosis but may also have self-identified with additional conditions. These differences should therefore be taken as a representation of individuals identifying with a diagnosis, without specific exclusion criteria.

Multi-sensory sensitivity and comorbidities

Subsequent analyses attempted to control for these comorbidities, and numerous conclusions can be drawn from these findings. Several clinical conditions remained significantly associated with heightened subjective sensory sensitivity upon controlling for other diagnoses. Of note, a reported diagnosis of autism was found to confer the greatest predicted increase in sensitivity, across both sensory sensitivity and sensory avoidance subscales. This is not necessarily surprising in the context of extant work regarding sensory differences a core feature of autism (APA, 2013; Leekam et al., 2007). However, it's direct comparison to other diagnoses, in terms of magnitude of sensitivity, is potentially impactful. For example, our analyses suggest that a diagnosis of autism may be associated with an over twofold approximate percentage increase in sensory sensitivity when compared to a diagnosis of anxiety alone.

The significance of other clinical conditions, when considered in the context of autism, is also noteworthy. For example, ADHD and autism are known to be highly comorbid (Rosen et al., 2018). Recent evidence has found ADHD traits in the general population to associate with an increased number of sensory difficulties (Panagiotidi et al., 2018), and further study reports that sensory hypersensitivities are increased in adults with a diagnosis of ADHD, regardless of co-occurring autistic traits (Bijlenga et al., 2017). The finding of our regression analyses, that ADHD associates with sensory sensitivity when controlling for an autism diagnosis, aligns with this finding, and replicates it at the diagnostic rather than trait level. This

supports existing calls for consideration of sensory sensitivity in the diagnostic process (Lane & Reynolds, 2019) and clinical management of ADHD, independent of comorbid autism diagnosis or self-identification.

Similarly, existing literature reports associations between autism and eating disorders, to find that autism diagnoses are over-represented in eating disordered populations (Huke et al., 2013). Further, individuals diagnosed with anorexia and bulimia endorse a greater number of autistic traits when compared to control participants (Dell'Osso et al., 2018). It is therefore of interest whether sensory differences, already reported in eating disordered groups (Bell et al., 2017; Zucker et al., 2013), persist when controlling for co-occurring diagnoses, including autism. Our analyses found this to be the case for bulimia, but not anorexia. This may have important implications for understanding and treating bulimic individuals, who may require sensory adjustments or additional support to engage with intervention, even where this condition is diagnosed in isolation. For example, acceptance and commitment therapy (which seeks to build acceptance of aversive feelings and reduce experiential avoidance; Juarascio et al., 2013) could include discussion of sensory experiences which are reported as difficult, particularly given this approach has already shown some efficacy in treating bulimia (Juarascio et al., 2013; Linardon et al., 2019). Anorexia did not significantly associate with sensory sensitivities in comorbidity analyses, and it could be speculated that this is because sensory differences reported in anorexia may more closely associate with autism. Indeed, recent evidence finds that individuals with anorexia and high autistic traits reported more sensory sensitivity than individuals with anorexia and low autistic traits (Kinnaird et al., 2020).

However, it could also be the case that sensory differences in anorexia, and indeed other conditions which showed significantly increased sensitivity but non-significant associations in regression analyses (migraine, OCD, PTSD), are accounted for by another comorbidity besides autism. For instance, anxiety is a known and common comorbidity amongst all of these conditions (Lantéri-Minet et al., 2005; Marucci et al., 2018; Menzies et al., 2021; Spinhoven et al., 2014), making it a clear possible mediator, particularly given its mediating effect upon subjective sensory sensitivity has already been demonstrated in migraine (see Chapter 2). Other comorbidities within and across these conditions are complex and copious, both in existing literature (Kessler et al., 2005) and the current sample (see Figure 3). Formal mediation models would therefore be required to determine the influence of specific diagnoses, for which the present study can provide theoretical basis.

Specific mention should also be afforded to synaesthesia, for two reasons. First, it is one of only two conditions producing different patterns of significance across sensory sensitivity and sensory avoidance subscales of the AASP; specifically, synaesthesia showed significant associations with sensory avoidance but not with sensory sensitivity. According to Dunn's model (Brown & Dunn, 2002) under which the AASP was developed, the sensory avoidance subscale relates to active (rather than passive) response strategies to cope with sensory input, and particular efforts to make the sensory environment more predictable (Brown, & Dunn, 2002). Perhaps therefore, sensitivities within synaesthesia are more related to control of the environment when compared to (and accounting for) other clinical conditions. Triggers of synaesthetic experience can be automatic and unpredictable (Mas-Casadesús & Gherri, 2017), which may underlie an enhanced need for synaesthetes to be able to predict their environment and thus their perceptual experiences. This explanation, although plausible, is speculative and would require further investigation. However, dissociations across these subscales are of interest.

Secondly, the nature of synaesthesia, being considered a "benign alternative form of perception" (Carmichael et al., 2019), makes it somewhat distinct from many of the other conditions considered in this work, which are largely psychological or neurodevelopmental in nature. Synaesthesia's association with clinical symptoms is also far less understood when compared to other diagnoses considered here, although increasingly investigated. For example, recent work in grapheme-colour synaesthetes reports co-occurrence with anxiety disorders (Carmichael et al., 2019). Additionally, a distinct and heritable profile of cognitive traits has recently been proposed which predisposes people to developing synaesthesia, but concurrently might act as a possible vulnerability to clinical conditions such as PTSD (Ward & Filiz, 2020). Complimenting this work on the potential relevance of clinical diagnoses to synaesthesia, our findings suggests that in part, the subjective sensitivities previously found in the condition (Ward et al., 2017) may be accounted for by clinical comorbidities. More investigation, targeting specific forms of synaesthesia, would be of interest to better understand these relationships.

Considering the potential cumulative effect of comorbidities, subsequent regression analysis found that each additional reported diagnosis is expected to be associated with an approximately 7% increase in sensory sensitivity, and an approximately 8% increase in sensory avoidance. This provides an estimate of the degree to which sensory sensitivities may be

present, *on average*, for individuals reporting a given number of clinical diagnoses. Although condition-distinct, this finding highlights the relevance of subjective sensory sensitivity to clinical conditions more broadly and speaks to a possible additive relationship between diagnoses and sensory experience.

Finally, gender was also found to significantly associate with the sensory sensitivity subscale of the AASP. Specifically, we found that those who self-identified as female or as gender non-binary had significantly higher subjective sensory sensitivity than those who identified as male. Evidence of gender differences in sensory sensitivity have previously been reported, with females found to be more sensitive than males in some samples (Engel-Yeger, 2012). However, this study appears to be one of the first in this field to include those identifying as non-binary. These findings are likely complex in their cause. It is possible that heightened sensitivity in this group may be related to measures broader than diagnoses considered here, including quality of life and mental wellbeing, which are reportedly reduced in non-binary individuals (Reisner et al., 2016) and known to associate with sensory sensitivities (Costa-lópez et al., 2021). It is also possible that identifying as non-binary is associated with more environmental awareness, contributing to subjective sensory sensitivity. Gender minorities are exposed to gender-related discrimination and stressors (Hendricks & Testa, 2012). It is conceivable therefore that subjective sensory sensitivity may increase due to an enhanced awareness of the environment and potential threats within it, when compared to other genders who do not face the same discrimination. This would require empirical investigation. However, regardless of cause, the potential additional impact of sensory sensitivities on daily life for female and gender non-binary individuals should be acknowledged, particularly given that this effect persisted above the effect of reported diagnoses.

Limitations

Important limitations in this work should be considered. In particular, possible implications of our sampling technique. First, a proportion of our sample were recruited via social media, via forums and pages relating to a clinical condition or area of neurodiversity. Research has not yet investigated the extent to which individuals who engage with such forums are representative of wider clinical populations, and therefore self-selection biases may be relevant. A certain level of digital literacy would also be required to participate in

online forums of this kind (Munger et al., 2021). Additionally, whilst the social media sample had a more varied age range, participants recruited from the university were largely young females. This predominance of female participants in our sample has implications for the extent to which our clinical groups are typical. For example, there is a characteristic male bias in autism diagnoses (Masi et al., 2017), yet in our sample only 15% of participants reporting autism were male. For these reasons, it is possible that effects of clinical conditions and their comorbidities on sensory sensitivities reported here may not be wholly representative.

However, it could be argued that these factors are only part of the within-condition heterogeneity already known to exist (Petrolini & Vicente, 2022). Further, a sample of individuals who are prototypical of a given condition is not only unlikely (and difficult to define) but additionally potentially problematic, in terms of limiting our understanding to only those who endorse a certain constellation of symptoms, and have certain characteristics (Petrolini & Vicente, 2022). That being said, a larger and more diverse sample of participants would certainly be necessary to strengthen these findings and ensure our understanding of subjective sensory sensitivities are relevant to the variety of individuals who might identify with a diagnosis.

An additional consideration is the collection of diagnosis related data. Participants were asked to report any diagnoses or self-identification with a clinical condition, in lieu of confirmation using medical records. There are several justifications for this. Firstly, we did not want to limit findings only to those able to access primary care and thus receive formal diagnoses, particularly given the survey was available worldwide; health services are diverse (Remschmidt & Belfer, 2005), and some diagnoses can be difficult and time consuming to obtain (Hezel et al., 2022). Additionally, in the context of recent moves towards self-identification with clinical conditions or neurodiversity in research (Angulo-Jiménez & DeThorne, 2019; Hswen et al., 2019; Pavelko & Myrick, 2015), this approach allowed us to be more inclusive. Finally, with the advent of dimensional models of psychopathology (Watson et al., 2022), it is possible that even if a given participant would not meet the DSM (APA, 2022) defined diagnostic criteria, their self-identification may reflect experience of subclinical symptoms which are still relevant to experiences of sensory sensitivity. Thus, findings presented here can still provide valuable insight. However, given that it is also possible participants may be misdiagnosed or misinformed in this sample, results should only be interpreted in the context of self-reported diagnosis.

Finally, it is worth noting the implications of the regression analyses used in this chapter. All diagnoses were included in a single model, to control for the influence of comorbidities. This approach is used empirically (e.g., Bekhuis et al., 2015; Jain et al., 2018), however it is unclear the extent to which this statistical control is representative. For instance, comorbidities are common (e.g., see Figure 3), and a diagnosis or condition existing in isolation therefore may be a minority circumstance. These analyses should therefore be considered in the context of this statistical consideration (see Chapter 8 for further discussion).

Future directions and implications

This work clearly defines subjective sensory sensitivity as a transdiagnostic symptom, which spans different forms of clinical diagnoses, with some evidence of unique, condition-specific associations. What is less clear however is the connection between these varied diagnoses which causes increased sensory sensitivity to manifest. Working hypotheses of sensory sensitivity focus on cortical excitability, arguing that our perceptual system aims to maximise behavioural sensory sensitivity (detection and discrimination of signals) whilst minimizing neural sensory sensitivity (metabolic energy in responding to a stimulus; Ward, 2018). Individual differences in sensory sensitivity may arise from different solutions to this balancing act, adopted due to differences in factors such as cognition or neural architecture (Ward, 2018). Broadly supporting this notion is evidence that, in response to the same stimulus, individuals who are more prone to sensory sensitivity (e.g., people with migraine or autism) have an increased BOLD response in visual cortex (Coutts et al., 2012; Samuel Schwarzkopf et al., 2014). However, the extent to which neural activation directly contributes to the ongoing experience of finding a stimulus aversive is not well understood. It is therefore not yet clear whether sensory sensitivity results from shared underlying features common across disorders in which it occurs (E.g., neural activation; Ward, 2018), whether and how it plays a causal role in the development of some disorders, or indeed whether the answer to this might depend on the condition in question.

Sensory sensitivity across clinical diagnoses may therefore not necessarily have the same cause but be a manifestation of differing solutions to the same underlying problem. However, as this theory also encompasses neurotypical variation in sensitivity, the tendency for those with these diagnoses to adopt a solution which results in such marked increases in

sensitivity also requires explanation. Further research which considers subjective, behavioural, and neural sensitivities, and how these concepts relate to each other across diagnoses, is therefore needed.

The mechanisms through which subjective sensory sensitivity spans such a broad array of clinical conditions could also be approached by considering how it associates with broader, underlying dimensions. The current study is strengthened by its consideration of comorbid diagnoses, however the extent to which we can understand for whom sensory sensitivity may be most problematic is limited by our incomplete understanding of how diagnoses might combine. For example, it is argued that the assumption of additivity (i.e., in someone with condition A and B, symptoms of both A and B will occur) is an oversimplification of what may be a complex interaction (Petrolini & Vicente, 2022). It is possible that symptoms such as sensory sensitivity may intensify, weaken, or even contribute to the development of novel features, under conditions of comorbidity. Although the present analyses controlled for the effect of co-occurring diagnoses, it did not investigate how conditions might combine to produce varying, and perhaps unpredictable, effects upon sensory experience. An alternative approach would therefore be to adopt a stratification method and consider how dimensions which may underlie several clinical diagnoses vary with, contribute to, or result from differences in sensory sensitivities. For example, known dimensions such as internalizing and externalizing (Kotov et al., 2017; Krueger & Eaton, 2015). Predicting sensory differences based on continuous, homogenous measures may be a more parsimonious approach than forming predictions based on a complex combination of heterogenous groups.

Distinct from possible causes of these cross-condition differences in sensory sensitivity are their clinical implications. Some of the findings presented here are not necessarily novel; associations between sensory sensitivity and diagnoses such as autism are widely known and investigated (Crane et al., 2009; Robertson & Simmons, 2015b). However, this work highlights the need for awareness of sensory differences across a broader range of diagnoses and provides concrete estimations for the extent to which an individual with a given diagnosis might differ in their sensory sensitivities *on average*, independent from the influence of other diagnoses. Descriptive analyses presented here, detailing patterns of how specific modalities may be affected, can also assist in identifying sensory environments which may be particularly challenging for specific diagnoses. These estimations should always be considered in an idiosyncratic context but can allow for an increased understanding of who sensory sensitivities

might be most impactful for, and in what ways, which can improve outcomes. For example, in helping the individual establish environmental conditions which support their sensory needs, or allowing for prediction and understanding of those which may be more challenging (Engel-Yeger & Dunn, 2011b). Additionally, existing interventions, such as those focusing on mindfulness (Hebert, 2016), can assist in building emotional resilience in response to challenging multi-sensory environments which cannot be modified. Occupational therapists in particular are well placed to advise and support with such intervention (Brown et al., 2019). In a broader sense, optional sensory alterations to existing public environments can also be relatively easy to implement (e.g., adjustable blinds, reduction of aversive sounds), and awareness of potentially problematic stimuli (E.g., visually distressing architectural design; Wilkins, Penacchio, & Leonards, 2018) may improve newly constructed locations. This research establishes that this may be particularly important in settings which individuals with clinical diagnoses are more likely to attend.

Summary

In summary, the present chapter has several conclusions. First, there are both similarities and differences in patterns of cross-modality sensitivity, highlighting that despite general increases in sensitivity across clinical diagnoses, condition-related differences in presentation may occur. Second, analyses found only specific conditions to associate with increased sensitivity when accounting for comorbid diagnoses. Of note, migraine, OCD, and PTSD showed non-significant associations with sensory sensitivity subscales, suggesting a role for other clinical characteristics in increasing sensitivity in these diagnoses. Other diagnoses, such as ADHD and synaesthesia, remained significant despite known overlap with diagnoses such as autism and anxiety. Importantly, this work only included investigation of 10 self-reported clinical diagnoses, meaning there is scope for further investigation in other relevant conditions (e.g., schizophrenia; Brown et al., 2002, tic disorders; Isaacs et al., 2022). However, it is clear that the role of comorbidities in sensory sensitivity should be acknowledged in future research. Investigation should also focus on better understanding the mechanisms through which atypical sensory sensitivity occurs across diagnoses, potentially making use of formal mediation or dimensional models to assist in simplifying complex heterogeneity. Enhanced understanding of subjective sensory sensitivity may improve outcomes and engagement in individuals for whom it is most impactful.

Chapter 4: A mixed methods approach to understanding the experience and impact of subjective sensory sensitivities

Introduction

As described in the General Introduction, subjective sensory sensitivities are common. As differences in sensory experience now form part of the diagnostic criteria for autism (APA, 2013), the nature and experiences of sensory sensitivities are particularly well studied in relation to this diagnosis. However, increased sensitivities are reported in a range of conditions, including anxiety disorders (Engel-Yeger et al., 2013; Isaacs et al., 2020), neurodevelopmental diagnoses (Rani et al., 2023), eating disorders (Bell et al., 2017; Saure et al., 2022), neurovestibular (Powell et al., 2020b), and neurological conditions (e.g., migraine, as described in Chapter 2), as well as in the general population (Robertson & Simmons, 2013). Subjective sensory sensitivity is therefore a transdiagnostic and pervasive experience, appearing across diagnostic categories and within general population samples.

Although not always conceptualised as a central symptom in clinical diagnoses, evidence indicates that sensory sensitivities play a negative modulating role in health and quality of life in a range of conditions. For example, increased subjective sensitivities are associated with decreased mental wellbeing and increased bodily pain in individuals with affective disorders, even when accounting for disorder-relevant coping mechanisms (Engel-Yeger et al., 2016). Similarly, in adolescents with persistent pain (Sinclair et al., 2019) or with migraine (Genizi et al., 2019, 2020), sensitivities associate with decreased emotional, social, and school-related quality of life. It is suggested therefore that sensory sensitivities are impactful in daily life, beyond the worsening of disorder-specific symptomology (e.g., compulsions in OCD; Lewin et al., 2015).

However, much of the existing body of work surrounding the daily impact of sensitivities has been focused around quantitative measures (e.g., Short-Form Health Survey; Ware et al., 1996). This limits our understanding of the effects of sensitivities to only those questions included in such questionnaires. For instance, from this data we cannot necessarily get an understanding of the contextual, specific, or nuanced ways in which sensory sensitivities impact functioning, beyond knowing it is negatively associated. There is therefore space for existing study to be expanded and complimented by qualitative insights, which acknowledge the participant as best placed to describe their own sensory world and its implications.

Existing qualitative exploration of the impact of subjective sensitivities are almost exclusively confined to individuals with autism (Daly et al., 2022; Jones et al., 2003; MacLennan et al., 2022a; Parmar et al., 2021; Robertson & Simmons, 2015). For example, based on a small focus group with autistic adults, Robertson and Simmons (2015) described the relevance of emotional and mental states to the experience of sensitivities (e.g., sensitivities being worsened by feelings of anxiety). Similarly, based on a thematic analysis of open text questions, MacLennan, O'Brien, and Tavassoli (2022a) described how sensitivities affect mood, increasing stress and anxiety. Limited qualitative work considering the impact of sensitivities exists in other diagnoses. In one such study, survivors of stroke described how sensory sensitivities affected their participation in daily activities, as well as made them feel fatigued, confused, and anxious (Alwawi et al., 2020). Despite sensitivities also associating with reduced social functioning, physical health, and mental wellbeing in the general population (Kinnealey et al., 2011; Lee, 2012), the qualitative impact of these experiences does not appear to be well-documented. The lived experience of sensory sensitivities in the range of individuals to which it is relevant therefore still warrants investigation.

Another relatively unexplored aspect of sensitivities across individuals is their nature. For instance, are patterns of sensitivities, in terms of affected sensory modalities, condition specific? The modality of problematic sensory stimuli has been investigated using qualitative approaches in autism (Robertson & Simmons, 2015b), ADHD (Wada et al., 2023), specific learning disorder (Wada et al., 2023), and acquired brain injury (de Sain et al., 2023), all of which find auditory and visual triggers to be most common. It is therefore of interest whether comparable results using qualitative data would be found across other clinical diagnoses (e.g., depression, anxiety, synaesthesia) and in general population groups.

This study therefore used a mixed-methods approach to investigate experiences associated with subjective sensitivities in a large, general population sample both with and without self-identified clinical diagnoses. The study had three key aims.

1. Using a diagnosis independent approach, the study sought to enhance understanding of the impact of increased sensory sensitivities on the daily lives of those who experience it; that is, what aspects of their life does it affect, if any, and in what ways?
2. Similarly, the study also sought to understand the ways in which people cope with or manage their sensitivities, and the factors or circumstances they feel worsen their experiences. Although limited, research is beginning to consider how sensory aspects

of the built environment can be adapted to be more accommodating (e.g., sensory adjustments in the workplace; Weber et al., 2022, or in public spaces; MacLennan et al., 2022b). Insights into effective and common forms of adaptations (and exacerbating factors) from individuals who are affected by sensory differences, regardless of diagnosis, would be highly valuable in informing this work to increase the accessibility of public environments.

3. Finally, the study also investigated how sensitivities compare across clinical diagnoses and areas of neurodiversity, and in individuals without any self-identified diagnoses. For example, are the cross-modal patterns of sensitivity and of positive sensory experiences similar across participant groups? As well as holding relevance to environmental adaptations for sensory differences, answering this question can also contribute to our understanding of underlying mechanisms, and whether similar theoretical approaches hold across diagnoses.

Methods

Participants

Participants were recruited via two methods. The first involved 591 undergraduate students at Cardiff University, who completed the online survey in exchange for course credit. The second recruitment method involved posting the survey link on various support and information forums on social media (Facebook, Reddit, Twitter). Forums were found by searching the condition name (e.g., "ADHD") and selecting associated groups or pages. Prior to distribution, the study's aims were clearly explained, and approval to post was sought from forum administrators or moderators. These participants (n = 174) were not compensated for participation. As thematic and content analyses were the focus of the study, only participants who provided qualitative responses were included; absent qualitative responses lead to the removal of 24 participants from the student sample, and 28 participants from the online sample.

Demographic information for each sample, and the final combined sample, is displayed in Table 1. The majority of the sample identified as female. The most frequent gender identities among those self-reporting as 'Other' included: gender queer, gender fluid, non-binary and agender.

Gender		**%**	
	Student (n = 563)	**Online (n = 150)**	**Total (n = 713)**
Male	10.5	16.0	11.6
Female	87.7	63.3	82.6
Other	1.6	19.3	5.3
Prefer not to say	0.2	1.3	0.4
Age	**Student**	**Online**	**Total**
Mean age (SD)	19.6 (2.7)	34.6 (14.6)	22.7 (9.4)
Age range	17-48	18-75	17-75

Table 1. Self-identified gender identity and age for student and social media participants, and the final combined sample.

Materials

All questionnaires were delivered online via Qualtrics survey. Demographic information was collected (age, self-reported gender), along with self-reported diagnosis of or identification with listed clinical conditions. Space was also provided to indicate conditions not pre-specified. Details of reported diagnoses are provided in *Appendix A*.

The survey began with four qualitative questions presented as follows:

"These questions are about your experiences with different sensory stimuli. Sensory stimuli can be anything in your environment which you can touch, see, smell, taste, or hear. It can also be things that might affect your movements or balance. We are interested in your reactions to these sensory stimuli. These reactions might be physical or emotional and can be positive or negative. There are no right answers – everyone responds differently to sensory stimuli, and we would like to hear about your individual experience (perhaps think of your different senses in turn). Please answer the following questions in as much detail as you feel comfortable with

1. *Can you describe the kind of reactions you have or behaviours related to sensory stimuli? These might be positive or negative. Please also provide any examples of particular types of sensory stimuli, scenarios, or environments which make you react this way.*
2. *Do you find yourself having to cope with or manage these reactions or behaviours? In what ways do they impact your day-to-day life, if at all?*
3. *Do you feel you are more or less sensitive to your environment than other people seem to be? What makes you think this?*

4. *[displayed if clinical diagnosis or area of neurodiversity reported] Do you feel your behaviours or reactions to sensory stimuli are related to your condition or neurodiversity? If so, how?"*

Quantitative measures of sensory sensitivities were also included in the survey but are not relevant to this analysis (*see Chapter 3*).

Analysis

A mixed-methods approach was used to answer our research questions.

To better understand the sensory experiences of our participants, with a particular focus on impact and wellbeing, coping mechanisms, and exacerbating factors, template thematic analysis (TA; Braun, & Clarke, 2021; Brooks et al., 2015) was used to define themes in our open-ended text responses. The approach has been previously used for data of this kind (Evans et al., 2020), and was selected due to its structured approach, with flexibility to meet the needs of specific research aims (Brooks et al., 2015). In this analysis, initial themes were developed based on existing theory and knowledge of the field. In acknowledging the participant as best placed to describe their own sensory world and its implications, *a posteriori* themes were also added following initial coding of the data and remained provisional throughout. That is, if an excerpt was not adequately represented by an existing theme, and had clear relevance to the research questions, themes were created or refined (Brooks et al., 2015). The use of both deductive and inductive approaches allowed us to be flexible in our understanding of the data, taking lead from the participants themselves in identifying meaning whilst also meeting specific information needs (e.g., identifying ways in which individuals cope with or manage their sensitivities). All themes, and any ambiguities, were discussed amongst coders and the wider research team.

Throughout analysis, the epistemological approach was one of critical realism (see Braun, & Clarke, 2013), which acknowledges the role and influences of the researcher, but maintains that phenomena exist independently of the coders and can be observed and described using the research process. Coders (A.P and R.O) consistently reflected on how their own sensory world, and experiences of clinical diagnoses and neurodiversity, influenced their interpretation and analysis of the data. Although a critical realist approach does not vilify this subjective lens, in some circumstances we felt it was possible that the experiences of the

coders might impact the meaning which could be derived from the text; for example, the research team discussed how our own experiences of subjective sensory sensitivities might create a baseline from which we interpret the experiences of others. Active efforts were therefore made to remain open to participants' own accounts of their sensory world.

Content analysis (Given, 2008), a quantitative and deductive approach, was also utilised to gain understanding of the nature of stimuli reported as problematic or positive. An *a priori* coding framework was established to capture the modality and valence of sensory stimuli reported by participants (e.g., the complete extract "I hate high pitched voices" would be coded as *auditory negative)*.

It was decided *a priori* that condition-specific inferences would only be applicable where n ≥ 20 individuals reported a given diagnosis, condition, or area of neurodiversity, to allow adequate power. Twelve clinical/neurodiverse conditions were reported by ≥20 individuals, namely: ADHD, autism, anorexia, anxiety, depression, bulimia, dyslexia, migraine, OCD, PPPD, PTSD, and synaesthesia. Subsequent quantitative analyses therefore centre on these conditions.

To allow for comparison of affected sensory modalities across clinical groups, where the absolute number of instances of sensory experiences reported was variable, proportions were calculated based upon coding counts (e.g., the proportion of total negative sensory instances that were auditory in modality).

In order to acknowledge the potential influence of comorbid diagnoses upon these proportions, an approach akin to a 'leave-one-out bootstrapping' was used, in which participants reporting each other clinical diagnosis were sequentially removed and proportions recalculated. This allowed for the calculation of error bars as an index of variability driven by comorbidities. Analyses were also repeated using proportion of individuals reporting each modality, rather than instances of each modality, to ensure consistency of findings (reported in *Appendix C*).

Results

Part 1: Thematic analysis

What is the day-to-day impact of subjective sensory sensitivities?

Our participants descriptions of the impact of their sensitivities were multi-faceted, with developed themes centring on sensitivities limiting social and functional capabilities, creating challenges in personal relationships, and being described as effortful and exhausting:

1. Sensitivities limit social and functional capabilities.

1.1 Sensitivities are perceived barriers to engaging in social or personal activities.

Specific insights included sensitivities impacting participants' perceived ability to socialise, either through being unable to interact with other people once overstimulated, or being unwilling to expose themselves to social settings which present sensory challenges (e.g., nightclubs, concerts, restaurants, pubs). Participants often expressed a desire to attend these events, but an inability to do so. Specific reference was also made to environments where social events usually happen for the individual, and the challenges these create:

"Usually when I am in a situation thats overstimulating my senses I find it difficult to socialise and interact with other. I can't focus and feel uncomfortable until I come back to my space."

"It makes it hard to go out in public. Communicating is like trying to figure out a new language each time. Crowds, loud noises, and too much movement makes me really uncomfortable or unsafe-feeling"

1.2 Sensitivities are perceived barriers to gaining and maintaining work or study.

Participants often described how sensory challenges such as lighting, sounds, or smells contributing to difficulties in the workplace or at university, to the extent where work was not completed, or academic attainment was affected. Specific references were frequently made to a lack of concentration or ability to focus, which may underlie these consequences for productivity:

"In school during my GCSE's I got very internally irritated and angry because I couldn't focus and could only here the shuffling of people's feet and clothing and their pens/pencils tapping against the table"

"I don't go out much, but when I do I always bring sunglasses and ear plugs or headphones. I get overstimulated very easily and it's very taxing for me to try and hold down a job. For this reason, I don't work."

1.3 Daily tasks are made challenging due to sensitivities.

Participants' ability to sleep, drive, and complete other functional tasks (e.g., shopping, using public transport) was described as limited by their sensitivities either directly due to the sensory challenges they present, or indirectly via the physical and emotional outcomes of experiencing hypersensitivity (e.g., tiredness):

"I avoid environments that trigger strong negative reactions, such as my kitchen. I try not to go in directly after someone else has used it to avoid the smell of food, and I try to use it alone to avoid hearing talking at the same time as the other uncomfortable stimuli. I struggle to wash the dishes, load or unload the dishwasher, look for food in the fridge, and cook complex meals because of this."

"I have to avoid many overwhelming situations just to get by, but many cannot be avoided and leave me exhausted and barely able to do basic activities of living for the rest of the day."

2. Sensitivities create challenges in personal relationships

2.1 Differences in sensory experience can create tension in relationships

Participants described how other people in their lives responded to their sensory reactions or needs, often referring to how others did not understand or felt their responses were unwarranted.

"I turn off lights because I hate them, that drives my Father insane and he yells at me all the time for turning off lights."

"I didn't realise I was different growing up, so when I'd tell my parents the radio presenter was making me sick, they'd think I was being dramatic."

2.2 Other people as a sensory challenge

Tension in relationships was also described where specific individuals, often in the home, were the source of difficult sensory experiences. Participants also discussed how having to withdraw from these situations or individuals caused guilt.

"My husband doesn't get it, takes it personally when I ask him to at least eat with his mouth shut but I get so so angry with him"

"My relationship with my partner and daughter is sometimes affected. It has been challenging to cope with sensory overwhelm with a small child. I have had lots of guilt over needing space from my child once overwhelmed."

2.3 Interpersonal consequences of feeling overwhelmed

Finally, participants also referred to how their responses to sensory stimuli impacted their relationships with others. For example, participants described becoming irritated and angry in response to sensory challenges and this affecting their subsequent interactions.

"It can cause me to want to cry or to want to yell at people."

"Repetitive noises cause extreme emotional fluctuations that… cause me to lash out unfairly at people"

3. Sensitivities as effortful and exhausting

Beyond functional and occupational impacts, consistent references were made by participants to the way that managing their sensitivities made them feel. Participants described the effort involved in planning to engage with, exposing themselves to, and recovering from sensory challenges, and how this made them feel drained or fatigued. Individuals described feeling tired after experiencing a difficult sensory environment, to the extent where they would withdraw to places of low sensory stimulation and high levels of control (e.g., their bedroom), to 'recharge'. Participants described the unrelenting nature of these experiences, often discussing how much of their energy and time was taken by managing their sensory needs.

"they impact my life daily and greatly. I'm usually not being able to force myself to go through it - and when I do, it takes a huge toll on me and my well-being and I need a lot of time to recover."

"sensory stimuli take up a lot of space in my everyday life and it can be a battle to try and not to feel pain, illness, or get overstimulated by everyday sensory inputs"

What do people feel are exacerbating factors for their sensory sensitivities?

1. **Tiredness**

Participants described how they felt more sensitive to sensory input when they were tired or had not slept:

"…voices, when I'm particularly tired feel like they're grating my skin. In a similar way, when I'm particularly tired some kinds of fabrics against my skin feel like they're scraping it"

"If I am outside of a migraine period and have less sleep, I can start crying on places like the Tube, a crowded shop, or the grocery store."

2. **Stress**

Similarly, participants frequently noted that they experienced greater sensitivity when they are stressed. A possible bidirectional relationship was also described, whereby feeling overwhelmed by their sensory environment further contributed to participant's ongoing stress.

"As an adult I started to notice a pattern. If I am stressed or overwhelmed, sensory sensitivity is much worse and can lead to a mental shutdown or outburst at home."

"I find the material of certain clothes (such as denim) uncomfortable but this does really have much of an effect unless I'm already having a bad day due to something else, like if I'm somewhere loud"

3. **Focused tasks**

Relevant to the impact of sensitivities on work and study, participants reported when they were engaging in these focused tasks, they felt more distractable or irritated by sensory information. If sensory stimuli were specifically described, they tended to be auditory:

"For example, when I am studying, completing an assignment or reading I tend to need complete silence to ensure I remain fully concentrated."

However, references were also made to decision making (a form of focused task) in intense visual environments:

"I shut down in places with too much visual input when I need to make a decision based on the information in that visual onslaught - this has happened when trying to order from a chaotic wall menu at a restaurant and while shopping for gifts at the mall"

4. **People or crowds**

Sensitivities were described as heightened when with other people or in crowded environments (e.g., supermarkets, shops):

"I get agitated and get overwhelmed by stimuli especially if they are all at once, if I am around a lot of people during this time then it makes it feel a lot worse."

"Regarding the mall/shop environment, I just leave the place immediately as the longer I stay there the more negative reactions will occur. It doesn't really impact my every day life, however in large crowds it may make me feel more uncomfortable."

5. **Symptom change**

With relevance only to specific clinical diagnoses or traits, participants described relationships between their symptoms (e.g., anxiety, depression) and their sensitivities:

"My anxiety affects my reaction to light as my vision tends to weaken as my anxiety peaks meaning that bright lights have even more of a harsh impact and I tend to feel more nauseas when I am anxious which leads me to have more of a reaction to potent smells."

"I feel I am more sensitive to the environment because of my OCD, but when I am coping well with the condition I would say I'm slightly less sensitive to the environment because my thoughts aren't too invasive."

6. Lack of prediction or control

Several participants discussed how they felt more impacted by the sensory environment when they could not predict it or control it. For some individuals this was a distinction between being at home (a highly predictable environment) versus being in public spaces. However, the sudden (and thus unpredictable) onset of specific stimuli, or the desire to control it, was also reported:

"Loud noises I can't control (ie irregular patterns) and don't know the source of are the most annoying to me."

"It is worse if the noise is a surprise. I am often frightened by loud cars, people dropping things etc It can take me 15-20 minutes to calm down afterwards, and my response to similar or smaller noises in that time will be much more pronounced."

How do people cope with their sensory sensitivities?

1. Limiting sensory input

Limiting sensory input took two forms. The first involved reducing sensory input through specific coping mechanisms including ear defenders, sunglasses, and cutting tags out of clothing:

"I wear sunglasses when driving, pretty much all of the time during daylight hours unless it's overcast and raining! I also only use low lighting and lamps at home as bright will give me nasty headaches."

"To cope with the sound overwhelming sounds I hear everyday form everyday objects and people I cope with having in earplugs almost all the time, even when Im alone in my home."

The second method of limiting sensory information was avoidance of the situation or stimuli completely:

"I like to be in quieter places and prefer my friends who speak quietly and are not ostentatious."

"When I was little I would refuse to wear socks with the glittery material on as I found it very itchy on my feet and would take them off quicker than they were put on"

2. Sensory stimulation

Participants frequently discussed using other sensory input to cope with the negative feelings that arise from their sensitivities. For example, using fidget toys or stimming:

"When in an overwhelming sensory environment- i.e., loud and busy- I tend to touch my hands in various ways: wringing them, clicking fingers etc."

Similarly, participants reported using enjoyable sensory stimuli (most commonly music) to distract or mask uncomfortable input:

"I use music when I am out running as this gives me something to distract from the feel of the pavement under my feet"

Forms of counterbalancing were also described; for example, where a participant might strike one side of their body in response to being struck on the other. Participants also described balancing intense sensory environments by not further contributing to them:

"I am not a fan of loud sounds, I usually get very quiet as my attempt to help the situation. I feel by not making any noise or auditory responses, I am not worsening the situation."

3. Self-regulation

Participants described a number of self-regulation strategies used to deal with their negative sensory reactions. These included trying to be accepting of their negative feelings, or using mindfulness and breathing techniques:

"I also had to learn some breathing techniques and how to calm myself so i dont completely freak out if i find myself in a situation with loud music or sounds that i can't escape."

Several participants also reported taking breaks from sensory challenges to manage their reactions or withdrawing from the environment completely. Distraction or immersion in video games, mobile phones, conversation, or other sensory stimuli (e.g., visually following something) were also frequent:

"I may mindlessly follow someone ahead of me in order to feel safer having something to lock onto so I can get through a crowd while being somewhat distracted."

Control and prediction were also relevant to coping with sensitivities. For example, through using structure or routine to maintain a predictable their sensory world, or considering the outcome of stimuli before they occur:

"I sometimes think of the outcome a different stimuli can have before I am exposed to it, therefore preparing myself"

Finally, negative health behaviours were also reported self-regulation strategies, such as skin picking, digging fingernails into their body, or using alcohol:

"I have managed much more successfully since I began treating my anxiety and depression, but before SSRIs I self-medicated with alcohol so I could tolerate places that would otherwise cause sensory overload"

4. The role of others

Other individuals were reported as a source of support in managing sensitivities. For example, participants reported discussing their sensory needs with those close to them (e.g., friends, housemates, family, employers) and receiving support or accommodations as a result:

"My roommates and friends are very accomodating when it comes to my noise sensitivity so it is not impacting me much."

Many participants reported suppressing their reactions in front of other people, citing concerns around how they would appear or how their reactions would affect others:

"I have a strong urge to cover my ears around loud noises but normal people don't do that so I suck it up."

Some participants also reported improvements in their ability to cope following professional therapy (e.g., exposure therapy).

Part 2: Content analysis

Figure 1 displays the proportion of negative sensory instances coded to each sensory modality in our participants, whilst Figure 2 displays positive sensory experiences.

In terms of negative instances, the pattern of proportions across conditions is broadly similar, with auditory, visual, and tactile modalities dominating participants' reports of their sensitivities, and smell, vestibular, taste and (in particular) proprioceptive sensitivities being less common. Auditory hypersensitivity was most frequently reported across all diagnoses except PPPD, for which vestibular hypersensitivity was most frequent.

Positive sensory experiences also showed a similar pattern across individuals both with and without clinical diagnoses. Auditory, tactile, and olfactory instances were most frequently reported. There was a descriptive decrease in positive visual experiences when compared to negative, and an increase in taste and proprioceptive instances.

The pattern of findings did not change when proportion of individuals rather than instances was calculated (see *Appendix C* for details).

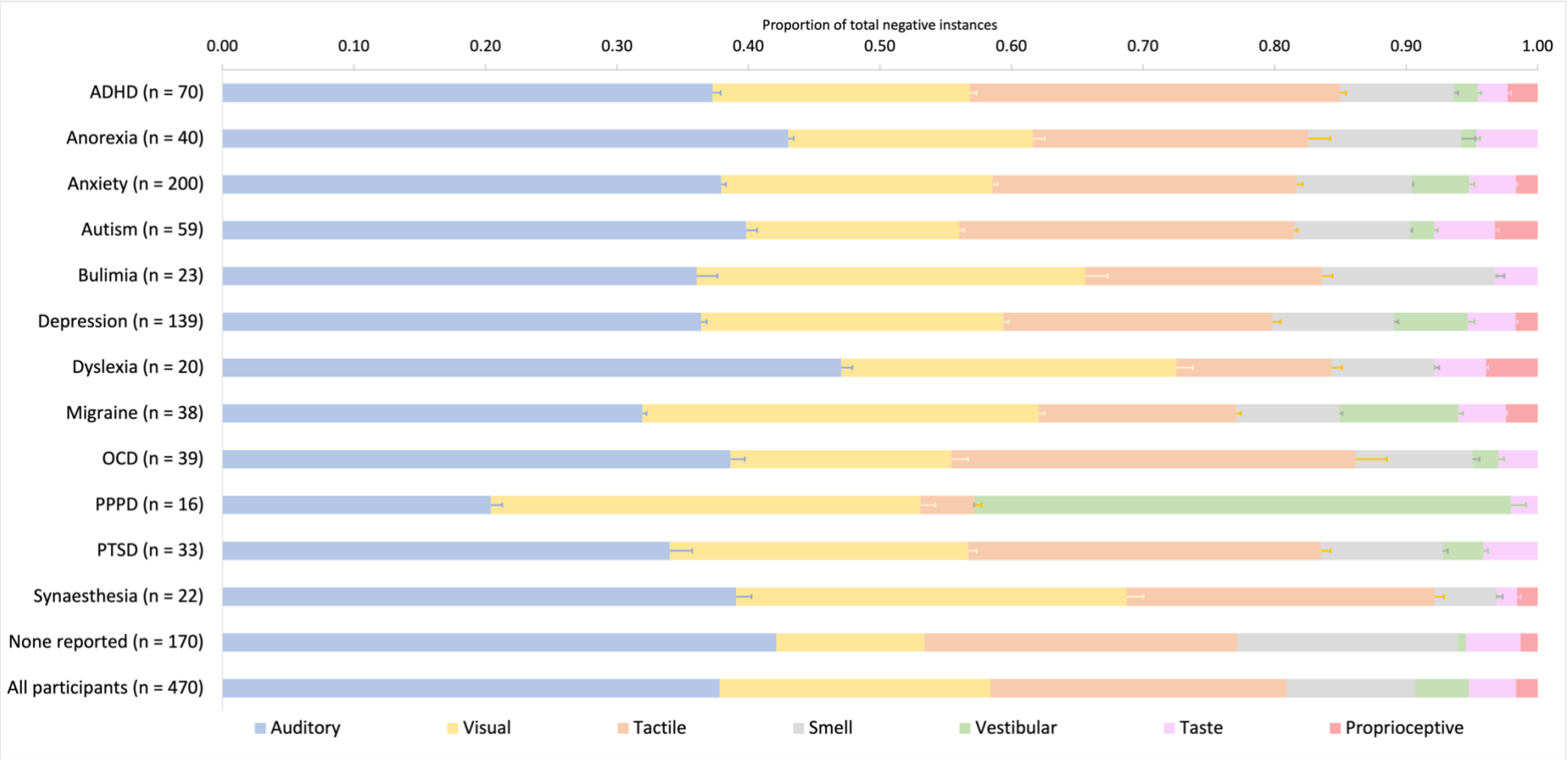


Figure 1. Proportion of negative sensory experiences attributed to each sensory modality across individuals reporting clinical diagnoses and those without, identified using content analysis. Error bars represent standard errors of proportions calculated using sequential removal of individuals reporting comorbid conditions.

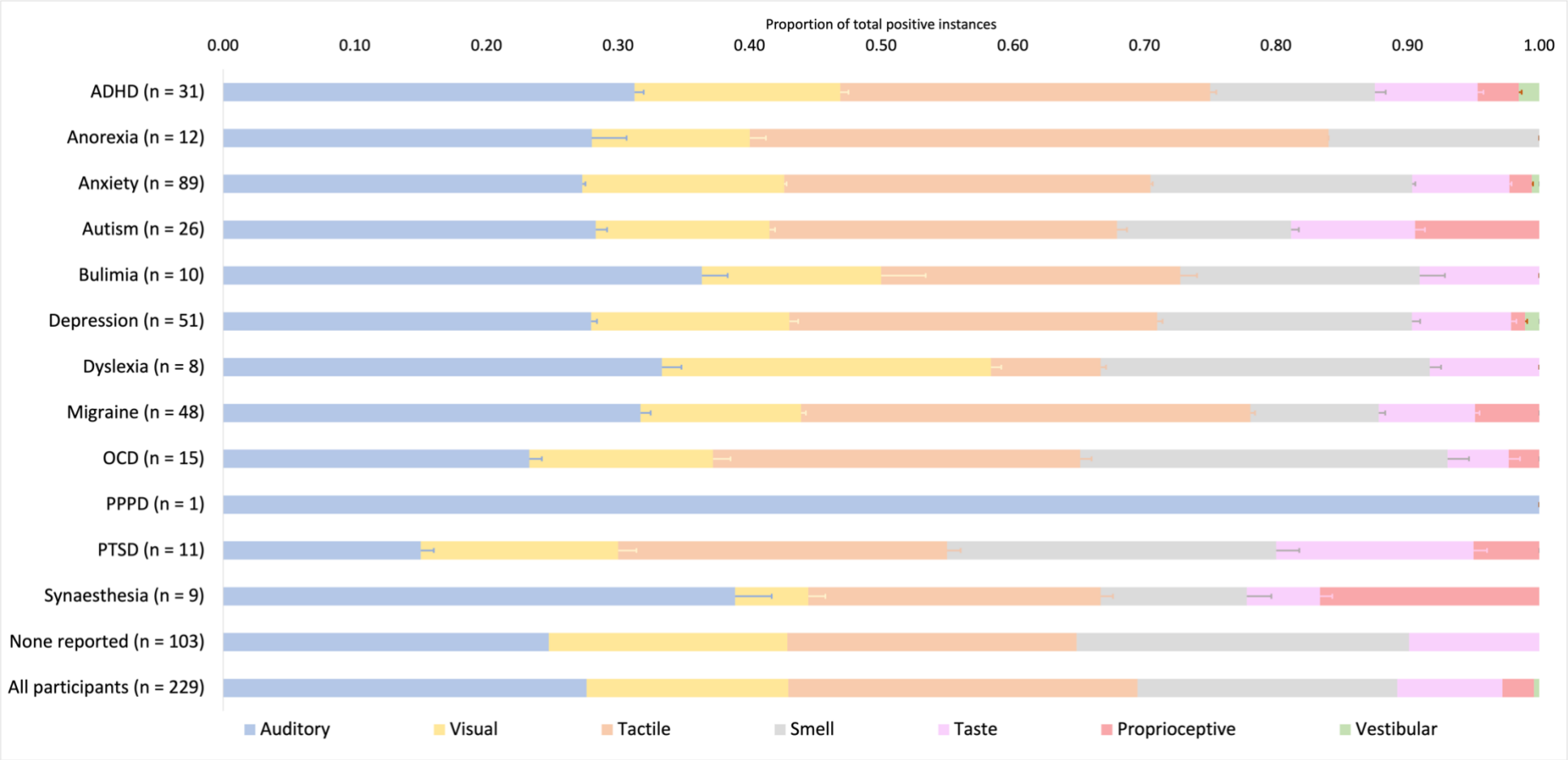


Figure 2. Proportion of positive sensory experiences attributed to each sensory modality across individuals reporting clinical diagnoses and those without, identified using content analysis. Error bars represent standard errors of proportions calculated using sequential removal of individuals reporting comorbid conditions.

Discussion

Previous research has established that subjective sensory sensitivity can play a negative modulating role in health and quality of life. However, beyond work largely focused in autism (Jones et al., 2003; MacLennan et al., 2022a; Robertson & Simmons, 2015), the qualitative, lived experience of the individual has not necessarily contributed to these conclusions. This study therefore used template thematic analysis to gain insight into the experiences of individuals who describe subjective sensory sensitivities. Content analyses were also used to investigate how the nature of sensitivities differs across individuals both with and without clinical diagnoses or areas of neurodiversity.

Thematic findings

The schematic presented in Figure 3 highlights the findings from the thematic analysis.

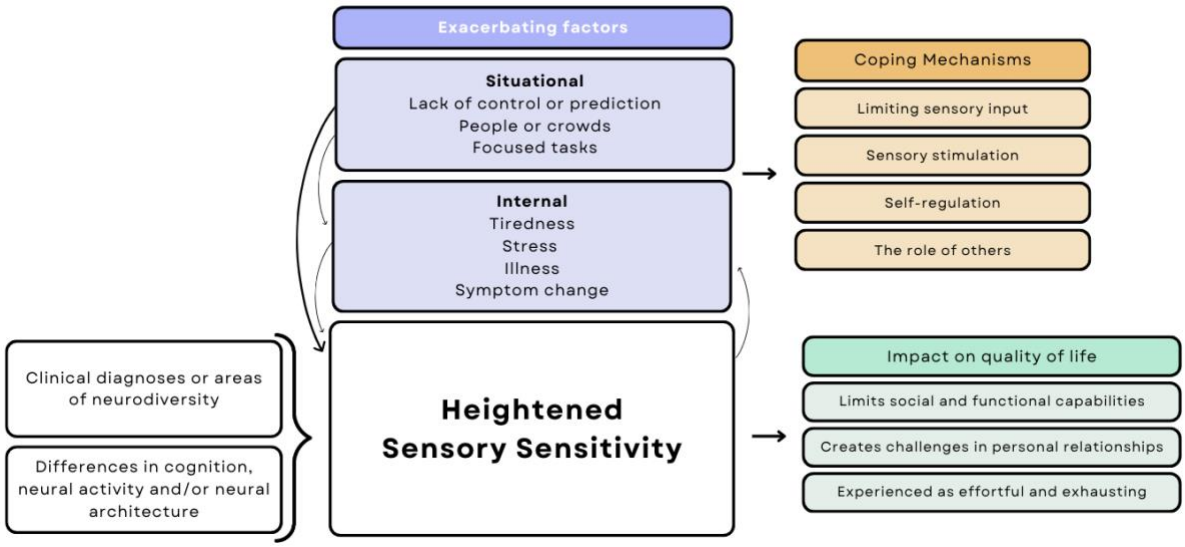


Figure 3. Schematic depicting findings from our thematic analysis, focusing on the factors which exacerbated sensory sensitivities for our participants, the coping mechanisms used, and the impact on quality of life.

Considering the coping mechanisms described by our participants, these were broadly separated into limiting sensory input (e.g., sunglasses to reduce brightness, or avoidance of brightness), sensory stimulation (e.g., stimming), self-regulation strategies (e.g., mindfulness) and the role of others (e.g., support from family). Our participants evidently use a range of different coping mechanisms, some of which converge with those found in study of individuals

with autism (MacLennan et al., 2022a), neurodevelopmental diagnoses (Wada et al., 2023), and hyperacusis (Greenberg & Carlos, 2018), including reducing or avoidance of sensory information, using enjoyable sensory experiences, and support from significant relationships. However, our participants also reported self-regulation strategies including mindfulness and breathing techniques, distraction, or immersion (e.g., in conversation, in games), and negative health behaviours (e.g., alcohol). The presence of additional strategies may be due to the increased clinical diversity of our sample (i.e., a broader range of diagnoses, and inclusion of individuals without them) or may be a result of a much-increased sample size.

The comparative efficacy of different coping mechanisms for individuals with sensory sensitivities cannot be established by this work however and is an important avenue for investigation. For example, avoidance of sensory challenges was commonly reported in our participants, but it is not clear to what extent avoidance may impact personal wellbeing. Within anxiety disorders, recent evidence suggests that behavioural reactions to feelings of anxiety (i.e., avoidance) may be more central to predicting quality of life than the presence of anxiety itself (Kirk et al., 2019). If applied to sensory sensitivities, it is unclear whether continuing to engage with the stimuli and using a different method of coping (e.g., stimming, mindfulness), where possible, would be more beneficial to wellbeing than avoidance. This may be particularly relevant when functional, social, and occupational activities are disrupted by avoidance of difficult stimuli, as was reported by our participants. Given some reports of using alcohol to engage with difficult sensory environments by our participants, it also appears important for future study to consider the prevalence and implications of negative health behaviours on the physical and mental health of individuals experiencing sensory hypersensitivity.

In terms of factors which exacerbate subjective sensitivities, participants described both situational and internal circumstances. One internal factor was a change in symptoms, applicable only to diagnoses where this is relevant (e.g., anxiety, depression, migraine). For example, one participant described having a particularly challenging day with their compulsions in OCD, and their ability to cope with sensory information thus being reduced. The directionality of these relationships, from the participants perspective, was often that a change in their symptoms resulted in a change in their sensitivities. Although this does not prove any mechanistic causality between symptoms such as anxiety and the experience of sensitivity, the perceived causal relationship described by our participants provides interesting

anecdotal evidence for future investigations. In particular, it offers a possible target for intervention, where for some individuals an improvement in their symptoms (e.g., compulsions in OCD) may offer some relief from their sensory sensitivities, ultimately improving wellbeing. These interventions would also have theoretical implications for the relationships between anxiety and sensitivities described in the General Introduction.

Other internal factors included stress, which when increased was described as heightening participant's sensitivities. Participants' descriptions of these experiences were not dissimilar to the 'Sensory Avalanche' described in work with individuals with Asperger syndrome by Smith and Sharp (2013), a cycle in which stress increases sensitivity, which increases stress, which further enhances sensitivity. Aligning with these qualitative reports, levels of cortisol have been associated with sensory experience in children with autism (Corbett et al., 2009), with specific increases in both cortisol and sensory sensitivities found in response to novel peer interaction (Corbett et al., 2016). Stress has also been associated with subjective sensitivities in general population groups (Redfearn et al., 2020). Longitudinal investigation of how ongoing fluctuations in stress, or the effects of stress reduction techniques, upon subjective sensitivities would be valuable in understanding the specificity of these effects.

Tiredness was also reported to influence sensitivities in a reciprocal sense. Specifically, tiredness was described as an exacerbating factor which enhanced participant's sensory sensitivities, but feelings of tiredness were also clearly described as an outcome of dealing with challenging sensory information and managing reactions (see theme: Sensitivities as effortful and exhausting)**.** A similar bidirectional relationship between fatigue and sensitivities has recently been described in a qualitative study of individuals with acquired brain injury (de Sain et al., 2023), supporting this experience outside of the population described here.

Participants described exacerbating factors could also be external, and included situations such as people or crowds (also found in previous work in individuals with autism; MacLennan et al., 2022b; Robertson & Simmons, 2018; Smith & Sharp, 2013), focused tasks, or a lack of control or prediction (e.g., new environments). Control and predictability are another example of where the content of our themes is interconnected; control and predictability were found to be relevant to both to circumstances that can worsen sensitivities (exacerbating factors) and improve them (coping mechanisms). For example, participants described wanting to be in control of materials that they touch or music they listen to, to avoid becoming overwhelmed. Participants also described using plans or routine to maintain a more

predictable sensory environment (e.g., eating a repetitive diet, wearing specific clothing). The importance of control and predictability to the experience of sensory stimuli is noted by previous work in the context of autism (MacLennan et al., 2022a; MacLennan et al., 2022b; Robertson & Simmons, 2015, 2018; Smith & Sharp, 2013), but the present study suggests control is also important in the experience of sensory sensitivity more broadly. There are potential, theoretical associations with the role of control and predictability and causal accounts of sensitivity (as described in the General Introduction), which centre around the idea that individuals high in sensory sensitivity are poorer at predicting their sensory world (Ward, 2018). Under this theory, a reduced ability to predict unexpected aspects of the sensory world may drive a desire to control it, as described by our participants.

In terms of impact and quality of life, our participants descriptions of the effect of their sensitivities on their daily lives were multi-faceted, with themes focusing on sensitivities as limiting social and functional capabilities, creating challenges in personal relationships, and being described as effortful and exhausting. Existing quantitative work aligns with these themes; sensory sensitivities have been found to be associated with reduced social functioning (Kinnealey et al., 2011), and shows clear negative associations with quality of life measures (Genizi et al., 2019; Lee, 2012). Our findings expand this work to individuals with and without clinical diagnoses, but also frames sensitivities as affecting personal wellbeing in a broader sense than has previously been established. For example, existing evidence finds that sensory sensitivities correlate with anxiety symptoms (Engel-Yeger & Dunn, 2011b). However, the personal impact described by our participants was far broader, with participants also explaining the mental load associated with sensory sensitivities and their management (e.g., planning, responding), guilt over inability to socialise or complete functional tasks, and feelings of shame or embarrassment about their sensory reactions, suggesting the mechanisms through which heightened sensitivities affect wellbeing are not limited to direct effects on anxiety.

Content analysis

The content analysis presented in this study investigated how the sensory modality associated with both negative and positive sensory experiences might differ across individuals, with results demonstrating that the pattern of modalities was broadly similar across diagnoses and participants reporting no clinical conditions.

In relation to negative sensory experiences, triggers in the auditory modality were most commonly reported across all groups except for those with PPPD, for whom vestibular triggers were most frequent (as would be predicted in this diagnosis). Sensitivities in proprioception, smell, and taste were the least commonly reported modalities. This was consistent even when content analysis was based upon number of participants reporting each modality (rather than number of reported instances, see *Appendix C*). This suggests that sensitivities in some modalities are more commonly experienced than others. It is possible to speculate about why this might be the case; for instance, visual and auditory triggers are less under direct control by the individual when compared to a sense such as taste. We cannot always control being exposed to bright lights or loud noises, but we are ordinarily able to control what we taste. Thus, exposure to uncomfortable visual and auditory stimuli may be more common.

In positive sensory experiences, tactile, olfactory, taste, and proprioceptive sensory inputs were more commonly reported, and positive visual experiences were less frequent. It may be the case that because positive sensory experiences are often sought out, sensory modalities that require direct contact (e.g., tactile, taste) or activation (e.g., proprioception) are more frequently described positively rather than negatively, compared to those that are often perceived from afar and can be more unpredictable (e.g., visual, auditory). Aligning with this, many examples of positive auditory stimuli centred around music, a stimulus within individual control. It should be noted that the available sample sizes were smaller for positive experiences, reflecting a tendency for participants to describe difficult sensory experiences over enjoyable ones (despite receiving encouragement to provide examples of both).

A clear conclusion from the results of the content analyses is that the nature of positive and negative sensory experiences is highly similar across a range of clinical conditions and in the general population. Extant work investigating the pattern and prevalence of cross modal sensitivities has largely centred on autism; for instance, in qualitative work, negative auditory and visual (MacLennan et al., 2022a;. Robertson & Simmons, 2015b) and positive auditory and tactile (Robertson & Simmons, 2015b) experiences are also the most commonly reported by individuals with autism. Specific reference to music as a particularly positive and soothing stimulus, as was reported here, is also found in autism literature (MacLennan et al., 2022a; Robertson & Simmons, 2015b). This supports the results of our content analyses and suggests that the pattern of sensory experiences across modalities may not be unique to autism.

Indeed, the particular prevalence of negative auditory and visual experiences is also found in individuals with ADHD (Wada et al., 2023), specific learning disorder (Wada et al., 2023), and acquired brain injury (de Sain et al., 2023), and the current study extends this in a larger sample size, to a broader range of clinical diagnoses, and in the general population.

There are clear theoretical implications for the similarity in patterns of sensitivities across individuals. Speculative claim could be made about condition specific sensitivities (e.g., gustatory sensitivities in eating disorders, visual sensitivities in migraine). However, other than in PPPD, the prevalence of sensitivities across modalities using this methodology has instead been shown to be comparable. Although this work did not investigate mechanism, this finding does lend credence to the possibility that the causes of subjective sensitivities may be similar across diagnostic categories, as a similar pattern of modality specific sensitivities arises.

It is worth noting the opportunity for comparison between the quantitative findings reported in Chapter 3 and the content analysis described here. For example, in the present chapter, visual sensitivities were more frequently reported by those reporting clinical diagnoses or areas of neurodiversity, when compared to those who report none. However, in quantitative analyses described in Chapter 3, there is not a clear increase in standardized visual sensitivity scores. Instead, there is either a condition-specific pattern of sensitivities (e.g., in migraine), or a general increase across modalities (e.g., in depression).

Reasons for these differences may be routed in methodology; for instance, the content analysis is derived from a count variable, which does not hold any information on the magnitude or nature of sensitivities. However, we might expect that when asked to openly describe their sensory experiences, participants would choose the ones that were most impactful or salient to them. Across most diagnoses, this seems to be sensitivity to auditory stimuli. In contrast, the quantitative results are based upon the Glasgow Sensory Questionnaire (GSQ; Robertson & Simmons, 2018), which includes three scored questions representing hypersensitivity in each sensory modality. Differences across groups may therefore be predominantly quantitative (in terms of degree of sensitivity across modalities) rather than qualitative (in terms of patterns of affected modality).

However, a low score on a particular modality subscale does not necessitate that the individual has low sensitivity in that modality. It might just be that the specific feature or stimulus that triggers their sensitivity is not included within the three items. Therefore, there may be a tendency for some individuals and groups to experience sensitivity to some features

but not others (e.g., bright lights but not repeating patterns). The current analyses centred on a count variable would mask these nuances, and the questionnaire measures used in Chapter 3 do not explore within modality subtypes.

Despite these differences, across both methodologies it is evident that sensitivities are common, transdiagnostic, and cross modal. However, investigation of within-modality trigger types, and their similarities or differences across diagnoses and areas of neurodiversity, will be an important avenue for future investigation, particularly in considering underlying mechanisms which may give rise to these differences.

Implications

As evidenced by the thematic analysis, our participants described the impact of sensitivities as affecting almost all facets of their daily life, including personal wellbeing, relationships, function, and occupation. Common coping mechanisms included avoidance of challenging sensory environments or situations, which may further contribute to impact (Robertson & Simmons, 2018) and reductions in social quality of life (Sinclair et al., 2019). There is thus a clear need for additional support for individuals who experience negative reactions to sensory stimuli.

Easing the burden of sensory sensitivities can take many forms, two of which will be discussed here. The first involves sensory alterations to existing public environments. Many of the circumstances reported by our participants as challenging included public spaces such as supermarkets, shopping centres, restaurants, and bars. It is possible to adjust these environments to better accommodate individuals with sensory sensitivities, with a view to reducing their emotional and functional impact. Alterations to existing public environments can be at the level of reducing sensory stimuli. For instance, adjustable blinds or reducing aversive sounds, or alternatively can occur via the provision of recovery spaces. For example, rooms or spaces which offer low sensory stimulation, but might include sensory stimuli which users can choose to engage with to self-regulate or recover (e.g., fidget toys, textures, lights). The use of breaks and sensory stimulation as a coping mechanism in our participants supports the need for these spaces and may improve upon the exhaustion described by our participants following engagement with difficult stimuli, as well as improving abilities to engage in functional or social occupations.

Beyond public leisure spaces, adjustments are also relevant and important to work and educational settings, such as offices and lecture theatres. Our participants often described how factors such as lighting, sounds, or smells contributed to difficulties with concentration in the workplace or at university, to the extent where work was not completed, or academic attainment was affected. There is limited research reporting changes in productivity as a result of sensitivities outside of study in autism (Kirchner & Dziobek, 2013; Landon et al., 2016) and ADHD (Schreuer & Dorot, 2017). However, this was a clear concern for our participants, suggesting existing places of work and study are not sufficiently accommodating. Sensory support of this kind is a matter of inclusion, with clear potential for important impacts on personal wellbeing, but additionally on academic and occupational outcomes. Adjustments may be idiosyncratic in some circumstances and may need to be discussed at an individual level, but considering recurring themes reported by individuals with sensory sensitivities is a beneficial start point. For example, the importance of control and predictability is evident in our findings, suggesting that the provision of private offices where possible, or the means to control environmental stimuli (e.g., blinds, music, lighting), would be beneficial. Similarly, other people and crowds were reported as an exacerbating factor. Workplaces and universities could therefore aim to prevent crowding (or provide notice of crowded events, to aid prediction) or allow for individual study spaces where possible or desired.

Interestingly, much of our findings align with work by MacLennan et al. (2022b) who described principles, based on focus groups with autistic adults, which could inform the improvement of public spaces for these individuals. For instance, as was found in this chapter, MacLennan et al. highlighted the need for recovery, the importance of predictability, the role of other people, and the impact of crowded spaces. This chapter's thematic analysis suggests that these principles could also improve sensory environments for a broader range of individuals, across diagnostic boundaries. Similarly, results from our content analyses finding the nature of sensitivities to be largely comparable across participants suggests that focusing adaptations upon key modalities (e.g., negative auditory or visual experiences, and positive auditory and tactile experiences) might similarly have widespread benefit.

Alongside physical adjustments, existing interventions can assist individuals in building emotional resilience in response to challenging multi-sensory environments which cannot be modified. For example, mindfulness-based skills of emotional regulation, self-awareness, and focused attention could be beneficial for individuals experiencing sensory distress, as has been

noted in previous work (Hebert, 2016). Themes identified in our participants also support this notion; some participants already report using mindfulness techniques as a method of coping, and others reported negative impact to which mindfulness could readily apply (e.g., irritability affecting others, an inability to concentrate). However, its efficacy for supporting sensory differences still requires investigation.

Limitations

These findings should be considered in the context of important limitations. First, although descriptions of coping mechanisms and the impact of sensitivities were explicitly prompted in our qualitative questions, exacerbating factors were not. Many participants spontaneously described circumstances which affected their sensory experiences, and it thus felt important to capture this insight within the thematic analysis. It is possible that if prompted via qualitative questioning, additional participants would have described exacerbating factors, potentially diversifying the resultant themes. However, this does not invalidate the insight provided by individuals in this work, and instead highlights areas where future study could extend and confirm these findings.

The diagnoses reported by our participants were also not confirmed by medical records or assessment, so their veracity cannot be determined. There are several justifications for this, as described in Chapter 3. In brief, we did not want to limit findings only to those able to access primary care and thus receive formal diagnoses, particularly as some diagnoses can be difficult and time consuming to obtain (Hezel et al., 2022). This approach also allowed us to be more inclusive of recent moves towards self-identification with clinical conditions or neurodiversity in research (Angulo-Jiménez & DeThorne, 2019; Hswen et al., 2019; Pavelko & Myrick, 2015). Additionally, within the context of dimensional models of psychopathology (Watson et al., 2022), self-identification with a diagnosis or area of neurodiversity, even if not confirmed, may reflect experience of subclinical symptoms which are still relevant to experiences of sensory sensitivity. Thus, findings presented here can still provide valuable insight but should be interpreted in the context of self-reported diagnosis. Future qualitative work acknowledging the impact of sensitivities in other diagnoses that were not considered here (e.g., schizophrenia, bipolar disorder, Tourette's) is also needed.

Finally, there are aspects of our sample that are demographically specific. For instance, a proportion of our sample were recruited on social media via forums and pages relating to a

clinical condition or area of neurodiversity. The remaining participants are predominantly young female students of Psychology at a UK university. This is not a limitation of the work (Braun & Clarke, 2021); the qualitative approach taken here was one which valued and prioritised understanding the realities of sensory sensitivities, in the context in which they are provided. However, the specific nature of our participants, and the ways in which they were recruited, provides an important backdrop upon which these findings should be considered.

Summary

This qualitative exploration described several themes which provide important insights into the lived experiences of individuals with sensory sensitivities. Our participants reported varied impacts of their sensitivities upon quality of life, including disruption to work or study, completion of daily tasks, creating challenges in personal relationships, and being experienced as effortful and exhausting. Themes surrounding exacerbating factors and the ways in which individuals cope with their sensitivities were also described. Content analyses found that the pattern of positive and negative sensory experiences across modalities was comparable across individuals both with and without different clinical diagnoses and areas of neurodiversity.

Several aspects of the current study echo existing findings in autism, suggesting that certain aspects of sensory experience are not unique to this diagnosis. Similarities found here also suggest that ongoing efforts to improve the accessibility of challenging sensory environments (Davidson, 2010; MacLennan et al., 2022b) has the potential to create positive change for a range of individuals. However, it remains important to ensure that individual voice is still incorporated. For instance, this work did not establish that specific environmental accommodations will suit a variety of individuals with sensory sensitivities, but implied that there may be consistent themes or areas of focus (e.g., auditory and visual triggers). Co-design with individuals with lived experience of sensitivities, and focusing on common, severe, and deliverable changes to public spaces, remains central to effectively accommodating needs and improving access. Our participants description of their sensory experiences additionally highlights a potential need to acknowledge sensory differences in the clinical management of a wider range of diagnoses, including consideration of how sensitivities might be affecting wellbeing and social or occupational participation.

Chapter 5: The Cardiff Hypersensitivity Scale: defining and measuring the four factors of visual hypersensitivity

Introduction

Visual hypersensitivity refers to first person reports of experiencing visual stimuli as distracting, aversive, or overwhelming (Ward, 2018). Triggers of this experience vary. For example, specific light is commonly reported as uncomfortable, including bright (Digre & Brennan, 2012), fluorescent (Loew et al., 2015), or flickering (Wilkins, 2016) lights. Spatial patterns can also induce visual sensitivity; for instance, striped patterns (Wilkins, 1995), blurred images (Hare & Hibbard, 2013), and certain styles of art (Penacchio et al., 2021) are known triggers. Similarly, fast, or intense movements (e.g., action films, crowds moving; e.g., Parmar et al., 2021) are known to cause discomfort in some individuals. Heightened visual sensitivity is associated with a variety of clinical diagnoses and areas of neurodiversity; for example, migraine (Wilkins et al., 2021), autism (Parmar et al., 2021), synaesthesia (Ward et al., 2017), depression (Qi et al., 2019), persistent postural perceptual dizziness (Powell et al., 2020b), depression (Digre & Brennan, 2012), and anxiety (Digre & Brennan, 2012). However, evidence also finds increased sensitivity to be common in the general population, with recent investigation even positing a possible role for visual sensitivity in predicting mental health outcomes (Hui et al., 2022).

As described in the General Introduction, specific causes of visual hypersensitivity are not yet well defined. However, stimuli known to be problematic are reported to have properties that deviate from those found in natural environments. For example, uncomfortable spatial patterns have an excess of medium-high spatial frequencies and a limited range of orientations, which are unlike the properties of the natural landscapes we have evolved to perceive (Juricevic et al., 2010). Other commonly reported triggers are also framed under deviations from natural spectra, including flickering or bright lights (Yoshimoto et al., 2017). These stimuli evoke large metabolic and electrophysiological responses (Huang et al., 2003; Orekhova et al., 2019), larger still in those susceptible to discomfort (e.g., individuals with migraine; Huang et al., 2003) supporting ongoing theories that visual hypersensitivity is a homeostatic mechanism designed to protect the brain from high metabolic load (Wilkins & Hibbard, 2014).

In investigating causes and correlates of visual sensitivity, much of extant literature has focused on specific triggers. For example, by using tests or questionnaires which assess only

aversion to pattern or to light (e.g., the Pattern Glare test, Hui et al., 2022, Qi et al., 2019, Ward et al., 2017; the Photosensitivity Assessment Questionnaire, Bossini et al., 2006; Bossini et al., 2009). Although valuable in understanding the underlying mechanisms of these experiences specifically, this approach is limiting as it does not recognise that individuals might have differing patterns or constellations of visual sensitivity triggers (e.g., pattern vs lights vs motion). This appears to be the case anecdotally, and is also reflected in qualitative reports where participants are not uniform in their reporting of visual sensitivity triggers (Parmar et al., 2021). There is increased awareness of the need to consider individual modalities of sensory sensitivity more carefully, to ensure intramodality differences are not masked (Tavassoli et al., 2014). It could be argued that this sentiment also extends to within modality differences, as more subtle distinctions within visual sensitivity may be obscured if only one aspect of the experience is considered. It therefore remains important to consider the possibility of subtypes, or factors, of visual sensitivity upon which people may vary. For instance, an individual displaying high levels of light sensitivity might not concurrently have high sensitivity to repeating patterns (although this may be more likely). Acknowledging and indeed measuring these differences will enhance our understanding of aetiology.

As discussed briefly in the General Introduction, existing self-report measures which assess visual sensitivity more broadly are not necessarily designed to investigate this nuance. For instance, the Adolescent/Adult Sensory Profile (AASP; Brown & Dunn, 2002), includes only six items assessing visual sensitivity, two of which are not necessarily specific to the visual domain (e.g., *"I limit distractions when I am working").* The subscale also does not include items which assess common triggers of sensitivity including striped or repeating patterns, and flicker. Similarly, the Glasgow Sensory Questionnaire (Robertson & Simmons, 2013) includes three questions which tap visual hypersensitivity, and does not assess sensitivities to motion or repeating patterns. Finally, the recently developed Sensory Sensitivity Scales (SeSS; Aykan, Vatansever, & Doğanay-erdoğan, 2020) includes a more comprehensive 10-item visual subscale; however, this measure also does not assess aversion to repeating patterns, despite this being a pervasive trigger (Braithwaite et al., 2013; Qi et al., 2019; Wilkins et al., 2021). Using visual sensitivity subscales measures such as these will provide important insight into subjective sensory sensitivities. However, to define possible factors of visual sensitivity, their correlates, and possible causes, novel measures are needed. This will enable us to understand

to what extent visual hypersensitivity experienced across groups of individuals is similar or different and investigate underlying mechanisms with more specificity.

The present study therefore seeks to develop a self-report measure of visual sensitivity, which builds upon existing work in several ways.

First, as mentioned, the measure will cover a broader range of visual sensitivity triggers, allowing for investigation of possible factors. After considering patterns in existing literature and qualitative data from a large population sample (n = 713, see participants described in Chapter 4), four factors of visual sensitivity were hypothesized which assess sensitivity to patterned or repeating stimuli (e.g., stripes, supermarkets; Wilkins, 1995, Popkirov et al., 2018, Robertson & Simmons, 2015), brightness (e.g., sunlight, bright lights; Aykan et al., 2020; Shepherd, 2010; Wilkins, 2016), strobing (e.g., flickering or strobing lights; Yoshimoto et al., 2017), and motion (e.g., high motion environments or media; Parmar et al., 2021, Ujike et al., 2008). Items to be used the novel measure were developed around these four hypothesized factors.

Second, the measure will frame questions in terms of functional impact. Many existing questionnaires use affective phrasing such as *"I dislike..."* or *"I am annoyed by…"*. Although emotional reactions to sensory input are relevant, responses to questions such as these can be more difficult to calibrate across participants. Instead of using degree of dislike as an indicator of visual sensitivity, respondents will be asked how often they engage in avoidance or coping behaviours (e.g., needing to wear sunglasses on a bright day). Similar approaches which assess sensitivity separately from emotional influence have been used previously (Aykan, Vatansever, & Doğanay-erdoğan, 2020).

Finally, many existing measures of sensory sensitivity are designed with specific populations in mind (e.g., autism; Robertson & Simmons, 2013). The novel measure developed here will instead be designed for use in both general population and clinical samples.

Study 1: CHYPS Version 1

Methods

Initial development

The initial version of the questionnaire (now referred to as the *Cardiff Hypersensitivity Scale*; CHYPS-v1) was developed according to the following principles:

1. Item wording is to be focused on functional changes as a result of sensitivity (e.g., avoidance) rather than affective changes (e.g., dislike).
2. Given many circumstances known to trigger visual sensitivity may also be challenging for individuals with anxiety (e.g., supermarkets, crowds), questions will be qualified so that affirmative responses were due to visual hypersensitivity specifically (e.g., *"…because I find them visually uncomfortable"*.)
3. Avoidance of the use of priming language where possible (e.g., *"ceiling lights are too bright" vs "I use soft lamp lighting…"*).
4. In acknowledging the participant as best placed to describe their own sensory world and its implications, allow for integration of participant feedback on the measure's interpretability and completeness at every stage.

Questions were developed using prior knowledge of visual sensitivity (e.g., from existing literature; Digre & Brennan, 2012; Kuze & Ukai, 2008; Parmar et al., 2021; Powell et al., 2021; Robertson & Simmons, 2015; Ward et al., 2017; Wilkins, 1995), in addition to triggers and coping mechanisms taken from a large qualitative dataset (see participants described in Chapter 4) in keeping with Principle 4. This qualitative work asked participants to report challenging sensory environments or inputs, and the ways in which they cope with them. Triggers and coping mechanisms in the visual domain were then collated, recurring concepts identified, and related questions targeting functional impact developed. Broadly, items derived from literature and qualitative data grouped into triggers relating to patterned or repeating stimuli, brightness, strobing, and motion. Table 1 demonstrates an example of the development process from trigger to item.

Trigger	Coping mechanism	Questionnaire item
Bright days	Wearing sunglasses	"I tend to wear sunglasses or a hat outside on bright days, even if it is cloudy"
Supermarkets	Avoidance	"I try to avoid going to supermarkets because I find them visually uncomfortable"

Table 1. Example of item development process for two items of the CHYPS-v1. Items were constructed from triggers and coping mechanisms derived from existing literature or qualitative data (from Chapter 4).

Items were subsequently reviewed by members the research team, as well as with collaborators both within and outside of the field, to ensure readability and interpretability. CHYPS-v1 included 26 items (see *Appendix D* for the complete measure), and the Flesch-Kincaid reading level for the measure was 80.2 ("Easy to read"; Flesch, 1948).

All items were responded to using a 4-point Likert frequency scale (0 = Almost Never, 1 = Occasionally, 2 = Often, 3 = Almost Always). Two additional qualitative questions were also included in the measure for further participant feedback in line with development Principle 4 (included in *Appendix D*). This was to ensure all questions were easily understood, and that key and common aspects of visual sensitivity were not overlooked.

Participants

To investigate the reliability, validity, and factor structure of CHYPS-v1, two samples were recruited to examine the consistency of psychometric properties across groups. The first sample involved 525 students at Cardiff University, who completed the online survey in exchange for course credit. The second method involved the online research platform Prolific (https://prolific.co/), upon which the general population can participate in research for payment. 350 participants were recruited using Prolific's representative sample function, in which the sample reflects the demographic distribution of a given population (in this case, the United Kingdom). The sample size is stratified across three key demographics (age, sex, ethnicity) using data from the UK Office of National Statistics. Eight participants from the student sample and one from Prolific did not provide complete data on the measures of interest and were therefore removed.

Demographic information for both samples is displayed in Figure 1. Mean age was 46.8 (SD = 20.2) in the Prolific sample and 19.6 (SD = 2.8) in the university sample. The most frequent gender identities among those self-reporting as 'Other' included non-binary and

agender. For clarity, these individuals will subsequently be referred to using the umbrella term gender non-binary.

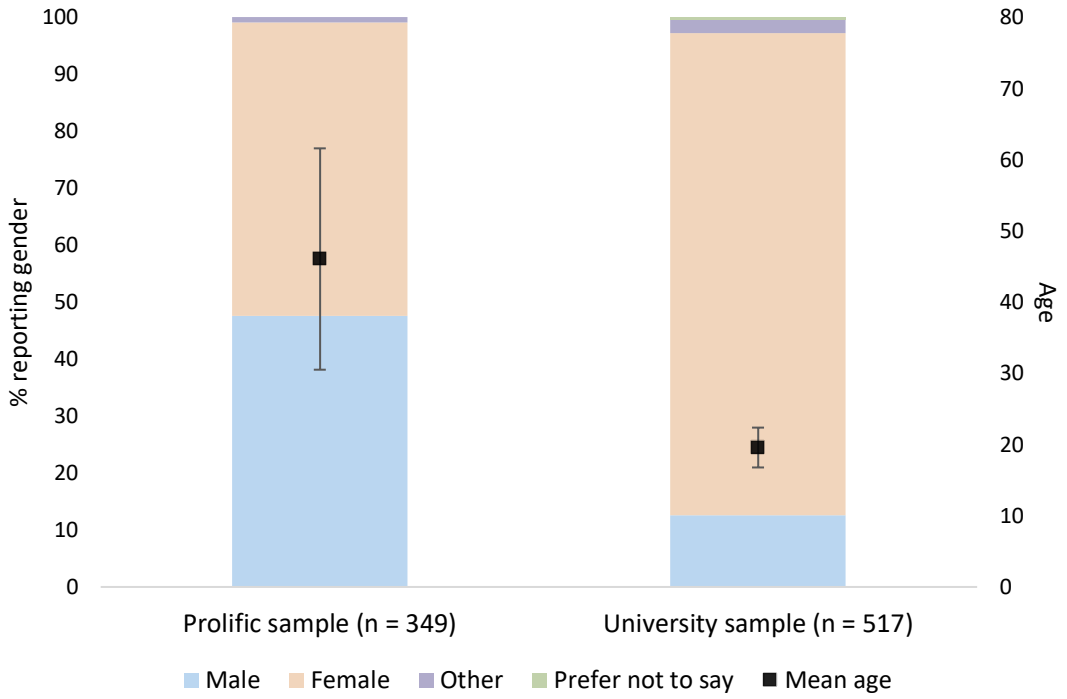


Figure 1. Demographics details (age, gender) for both Prolific and university samples.

Measures

All questionnaires were delivered online via Qualtrics survey. Demographic information was collected (age, self-reported gender), along with self-reported diagnosis of or identification with listed clinical conditions. Space was also provided to indicate conditions not pre-specified. Details of reported diagnoses are provided in *Appendix A*. Participants completed the CHYPS-v1, along with additional measures not reported here.

Statistical analyses

Data preparation, descriptive analyses, bivariate correlations, and reliability measures (Cronbach's α and MacDonald's ω) were completed using Jamovi (The jamovi project, 2022). Factor analytic procedures were completed in RStudio (R Core Team, 2022) using the *psych* package (Revelle, 2023). Appropriateness of the data for factor analyses was determined using Kaiser-Meyer Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. Bartlett's test determines whether there are sufficient relationships within a data set to

support factor analysis (i.e., the correlation matrix is not an identity matrix), whilst the KMO measure of sampling adequacy assesses common variance and is an indicator of whether latent factors may be present. Both tests supported the use of factor analysis (Dziuban & Shirkey, 1974) in both samples.

Multiple models of subjective visual sensitivity were compared: (1) a single factor, unidimensional model in which all items load on one factor (2) a multidimensional, correlated factors model (3) a multidimensional, bifactor model where items load on a general factor as well as specific factors. Bifactor models were specified as they are beneficial in their ability to examine differential relations of general and specific factors with external variables, and additionally separate variance to investigate the role of particular constructs in general and specific factor loadings (Bornovalova et al., 2020).

Where model specification allowed, number of plausible factors was identified using parallel analysis and oblimin rotation, and alternative solutions (e.g., one few factor) evaluated (Watkins, 2018). Principal axis estimation was used as it makes no distributional assumptions (Baglin, 2014; Watkins, 2018), and models were compared using fit statistics including Bayesian Information Criterion (BIC) and Root Mean Square Error of Approximation (RMSEA). However, caution should be used when using fit statistics to interpret bifactor models, due to risk of overfitting (Bonifay et al., 2017a; Greene et al., 2019). Models were therefore also assessed in terms of interpretability and parsimony of factors in the context of existing theory, as well as the strength of each factor (e.g., factors that included less than three items were not retained; Costello & Osborne, 2005). Items were retained if their loading was equal to or greater than .30 (Costello & Osborne, 2005), and cross loadings were absent or had a difference of greater than .15 between factors (Worthington & Whittaker, 2006).

Macdonald's ω is reported as an indicator of internal consistency, as it is argued to provide a less biased estimate than Cronbach's α (Dunn et al., 2014). However, alpha is also reported for completeness, where 0.70 - 0.79 is considered fair, 0.80 – 0.89 good, and > 0.90 excellent (Nunnally, 1994).

Results and Discussion

Factor structure

Fit statistics for all assessed models are displayed in Table 2. A bifactor model with 3 specific factors did not converge in the student sample, and thus is not reported. Across both samples, optimal fit (according to fit statistics) was identified as a bifactor model with four specific factors. However, these models were not well defined; in both bifactor solutions, factor loadings fell below .30 in some cases, and the removal of these items would result in weak factors (Costello & Osborne, 2005). As a result of poorly defined factors in the bifactor solution, a four-factor correlated factor model was identified as optimal. The factor loading structure in this model was similar to that of the bifactor solution, but with reduced loadings in the bifactor model likely due to variance accounted for by the general factor (Hoffmann et al., 2023). Some of the weaker loading items (e.g., movement in corner of eye, TV or film with fast motion) were also not retained in the bifactor model, also likely due to variance accounted for by the general factor.

Prolific sample (*n* = 349)							
Specific Factors	**Model Type**	***X*²**	***df***	**RMSEA**	**95% CI**	**Cumulative %**	**BIC**
0	Unidimensional (13 items)	489.87	65	0.14	0.13-0.15	42.47	109.29
4	Correlated factor	106.82	41	0.07	.05-.08	59.67	-133.24
3	Bifactor	214.22	52	0.09	0.08-0.11		-90.39
4	Bifactor	84.09	41	0.06	0.04-0.07		-156.09
5	Bifactor	51.45	31	0.04	0.02-0.06		-130.15
University sample (*n* = 517)							
Specific Factors	**Type**	***X*²**	***df***	**RMSEA**	**95% CI**	**Cumulative %**	**BIC**
0	Unidimensional (17 items)	883.08	135	0.10	0.10-0.11	36.24	39.59
4	Correlated factor	273.43	87	0.06	0.06-0.07	49.28	-270.15
4	Bifactor	246.99	74	0.07	0.06-0.08		-215.22
5	Bifactor	145.4	50	0.06	0.05-0.07		-166.91

Table 2. Fit statistics across model types in both Prolific and university samples. *Note* RMSEA = Root Mean Square Error of Approximation, BIC = Bayesian information Criterion.

In the final four-factor correlated factors model, 12 items were not retained due to weak loadings or high cross-loadings in the Prolific sample, and 9 were not retained in the student sample. Final factor loadings are displayed in Table 3. The four factors were conceptually similar in both samples. Specifically, they were readily interpreted as being associated with sensitivity to Pattern, Brightness, Strobing, and Intense Visual Environments

(IVE; see Table 3 for abbreviated item loadings). Although many of the items performed similarly across participant groups, (e.g., items relating to needing to wear sunglasses, getting headaches on bright days, and using a shade when driving loaded onto the same factors in both analyses), there were some differential loadings. For example, additional items loaded onto the brightness factor in the student sample (e.g., discomfort in response to flickering sunlight and the lights found in tunnels), which were not retained in the Prolific sample. However, these item differences were theoretically consistent (i.e., lights in tunnels loaded into a relevant factor, Brightness).

Item	Strobing		Pattern		IVE		Brightness	
	Prolific	University	Prolific	University	Prolific	University	Prolific	University
Flickering lights or screens	0.58	0.55						
Strobing lights on TV or film	0.68	0.33						
Strobing in venues (e.g., theatres, clubs)	0.66							
TV or film with fast motion	0.44			0.44				
Flickering lights or screens (H)		0.85						
Bright lights (H)		0.56						
Flickering in environment (H)		0.45						
Distortions in repeating or stripey patterns			0.45	0.54				
Repeating or stripey patterns (H)			0.87	0.75				
Repeating or stripey patterns			0.67	0.78				
Movement in corner of eye			0.45					
Supermarkets					0.82	0.68		
Supermarkets (H)					0.78	0.69		
High motion environments					0.51	0.69		
Moving objects (H)						0.56		
Wearing sunglasses if cloudy							0.79	0.61
Use a shade when driving							0.72	0.64
Bright days (H)							0.57	0.58
Sunlight flickering through trees								0.56
Tunnel with lights inside								0.46

Table 3. Factor loadings for Prolific and University samples, resulting from exploratory factor analysis (parallel analysis, oblimin rotation). *Note*: item names are approximations of the complete CHYPS-v1 items which can be found in *Appendix D. (H) indicates that the item asked whether the stimuli triggered a headache.*

Reliability and validity

Table 4 displays descriptive statistics for total and subscale scores across both samples, along with Cronbach's α and Macdonald's ω. Mean scores in Table 4 are standardized to the same scale to account for differing numbers of items contributing to the scales across and within samples. This allows for comparison of magnitude across groups. Across samples, descriptive statistics followed a similar pattern. Items associated with the brightness subscale were most commonly endorsed, and IVE items the least.

Reliability as measured by α and ω was acceptable in all subscale and total scores (where acceptable = α > .70 (Nunnally, 1994) and acceptable ω > .70 (Ponterotto & Ruckdeschel, 2007)). Subscale correlations were largely similar in magnitude across participant groups and did not suggest factor redundancy.

Prolific sample (*n* = 349)						
Scale	**M**	***α***	ω	**1**	**2**	**3**
Total	7.4	0.89	0.90			
1. Strobing	1.8	0.79	0.80			
2. Pattern	1.5	0.85	0.86	0.64		
3. IVE	0.8	0.82	0.83	0.49	0.59	
4. Brightness	2.2	0.77	0.78	0.44	0.52	0.49
University sample (n = 517)						
Scale	**M**	***α***	ω	**1**	**2**	**3**
Total	12.3	0.88	0.89			
1. Strobing	2.3	0.84	0.84			
2. Pattern	1.6	0.77	0.78	0.59		
3. IVE	0.9	0.79	0.79	0.48	0.45	
4. Brightness	2.2	0.77	0.77	0.54	0.47	0.39

Table 4. Summary statistics and reliability indices for each subscale calculated based on each sample's respective factor structure, and associated Spearman correlations between each subscale. Note. α = Cronbach's alpha, ω = Macdonald's omega, IVE = intense visual environments.

CHYPS-v1 thus shows evidence of theoretically sound factor structure and good reliability across two large samples. However, aspects of this measure require improvement. For example, although factor structure was conceptually consistent in both student and Prolific samples, specific items loadings were not consonant. As mentioned, these item differences were not theoretically at odds; generally, items retained in one model were similar to items retained in the other. This is reassuring in terms of the conceptual stability of the measure, however, poses a challenge in finalising items and ensuring appropriateness and

consistency across varying samples such as these. Similarly, item loadings were poor in the bifactor models, despite favourable statistical indices (RMSEA, BIC). It is possible that a general factor, as is defined in these models, is not appropriate for this data or construct. However, it is also possible that factors of visual sensitivity were not sufficiently defined by our 26-item measure. For instance, only three items relating to pattern sensitivity consistently group together, which is not conducive to a strong factor (Costello & Osborne, 2005). Given the evidence for a probable pattern factor provided by these analyses, adding additional items to bolster this construct are warranted, both for improvement of the measure, and for a more thorough consideration of the general visual sensitivity factor.

To investigate possible differences in participant interpretation, and derive novel questionnaire items, participants qualitative feedback was consulted. Participants were asked to provide feedback on the measure's interpretability and completeness. Across both samples (n = 866), no participant indicated that any of the items were unclear or difficult to understand. A very small minority (n = 3) of participants reported some repetitive wording. In terms of completeness, 347 participants across both samples provided examples of visual stimuli they felt were uncomfortable and were not included in the CHYPS-v1 measure. These responses were manually collated into common themes, which broadly included: glare (e.g., light reflecting off water), movement (e.g., motion associated with first person video games), contrasts in brightness (e.g., headlights at night), and colour (e.g., too much colour at once). In keeping with our fourth development principle, this participant feedback was incorporated into new questions to be included in version 2 of the measure, with additional focus upon factors which required strengthening (e.g., Pattern). Question structure and wording was also re-reviewed by the research team to avoid differences in understanding which may give rise to discrepancies in item loading.

In summary, CHYPS-v1 displays promising psychometric properties and suggests four factors of visual sensitivity which are consistent across two samples. However, the strength of factors could be improved, both in terms of item loading and item consistency. Participant feedback also suggested coverage of visual sensitivity triggers (i.e., construct validity) could be improved. Additional items were therefore added; it is hoped this revised version will improve upon our ability to evaluate visual sensitivity using this measure.

Study 2: CHYPS Version 2

Version 2 development

For CHYPS-v2, 16 additional questions were developed from two key sources: participant feedback on completeness and interpretability of CHYPS-v1, and reflection and careful consideration by the wider research team on the interpretation of the existing questions. Figure 2 displays the feedback derived from these sources, the resulting action taken, and example item(s) of where this was implemented.

For example, in some cases, an individual item from CHYPS-v1 asked about two distinct visual sensitivity triggers. This presents a challenge for respondents who experience discomfort in one situation but not another and may create variation in responding that is not due to discomfort specifically. Items such as these were therefore split, to encourage more consistent and accurate responding. The research team also reflected on how the wording of some questions did not prevent participants from responding based on the frequency of exposure to a given situation, rather than their reaction when it is experienced. Item wording was therefore adjusted, and additional pre-questionnaire instructions included, to avoid this. The complete 42-item CHYPS-v2 is provided in *Appendix E*.

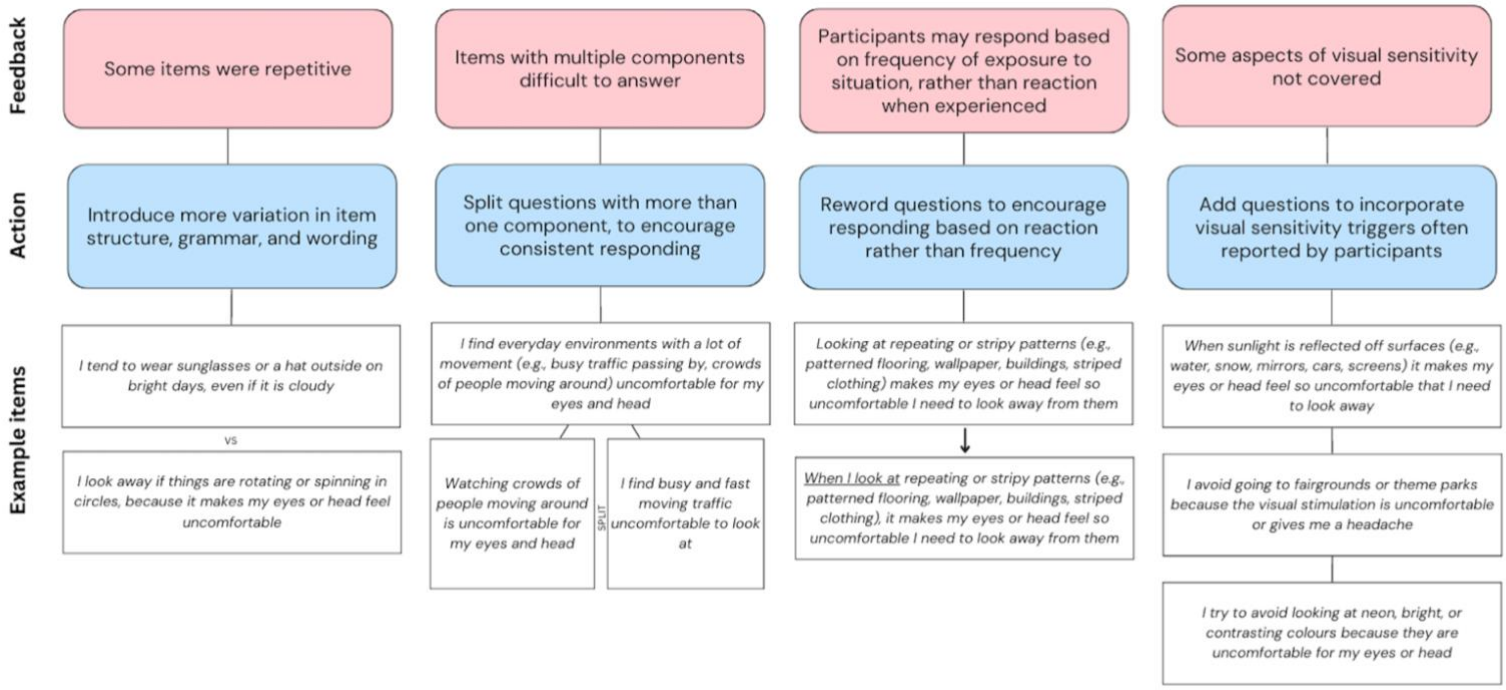


Figure 2. Schematic of the feedback and resulting actions taken to develop CHYPS-v2. Pink shapes denote feedback, blue denotes action taken, and example items from CHYPS-v2 are given in white.

Alongside investigating the dimensional structure of the CHYPS-v2, Study 2 also sought to evaluate the test re-test reliability, as well as divergent and convergent validity of the measure.

Participants

As in Study 1, the online research platform Prolific was used to recruit 800 participants. Sample size was improved from previous experiments to increase power and align with the proposed ratio of 1:10 between scale items and respondents (Nunnally, 1994). Prolific's representative sample function was utilised as before to recruit participants who are stratified according to demographics of the United Kingdom. Three participants were removed from analysis as they responded incorrectly to checks of attention and/or comprehension. Seven participants had missing data for the CHYPS-v2 and were therefore removed from bifactor analyses. Demographic details of the remaining participants are displayed in Table 4.

Gender	**%**	**Ethnicity**	**%**
Male	48.2	White	87
Female	50.4	Black	3.2
Other	1.3	Asian	7.1
Mean Age (SD)	**Age Range**	Mixed	1.5
45.6 (15.5)	18-88	Other	1.3

Table 4. Demographics for Study 2's representative Prolific sample (n = 790). Gender data was missing for one participant, age data was missing for six participants.

Following participation, all participants were invited to take part in a second study which aimed to assess the test re-test reliability of the CHYPS-v2. This study was advertised via Prolific 14 days after the initial study, in keeping with literature recommendations (e.g., Little et al., 2011; Marx et al., 2003). A total of 658 individuals took part, 653 of which had complete data for CHYPS-v2 at both timepoints. This subset of participants had a mean age of 47.3 (15.2), 48.9% identified as male, 50.1% as female, and 1.1% as another gender identity.

Measures

As in Study 1, a Qualtrics survey was used to deliver all measures. Age, self-reported gender, and previous clinical diagnoses or reported areas of neurodiversity were collected. Details of reported diagnoses are provided in *Appendix A*. Participants completed the 42-item

CHYPS-v2, (see *Appendix H* for the measure's instructions and included comprehension check) along with the following additional measures to assess convergent and divergent validity:

Adolescent/Adult Sensory Profile-Visual (VAASP; Brown & Dunn, 2002)

The AASP is a self-report measure of sensory function as it relates to Dunn's model (Dunn, 1997). Items of the AASP assess four domains of sensory experience across six modalities. As this measure was included to assess convergent validity, only the six items relating to visual sensitivity were utilised in the present study. Subscales such as these have been used in previous work investigating modality specific differences (Schulz & Stevenson, 2021; Schulz & Stevenson, 2020). Example items from the visual sensitivity subscale include *"I become bothered when I see lots of movement around me (for example, at a busy mall, parade, carnival)".* Responses are provided on a five-point scale spanning from "Almost Never" to "Almost Always".

Sensory Sensitivity Scales-Visual (SeSS-V; Aykan, Vatansever, & Doğanay-erdoğan, 2020)

The SeSS is a self-report measure of sensory sensitivities across three domains: visual, auditory, and somatosensory. As an additional indicator of convergent validity, only the 10-item visual subscale was included in the present study. Participants are asked to respond on a five-point scale from "Never" to "Always". The SeSS, similar to our novel measure, sought to develop items that were relatively independent from the emotional features of sensory sensitivity (e.g., "*I sit at home in dim light"*). Cronbach's α for this subscale was adequate α = 0.86 (Aykan, Vatansever, & Doğanay-erdoğan, 2020).

Migraine Screening Questionnaire (MS-Q; Láinez et al., 2005)

The MS-Q includes five items which ask individuals about migraine episodes experienced in their lifetime, each with a yes/no response. Example items include "Do you usually suffer from nausea when you have a headache?" and "Does light or noise bother you when you have a headache?". The MS-Q shows adequate validity and reliability (Cronbach's α=0.82; Láinez et al., 2005).

Niigata PPPD Questionnaire (NPQ; Yagi et al., 2019)

The NPQ uses 12-items to assess exacerbating factors of Persistent Postural Perceptual Dizziness (PPPD), a condition with theoretical relevance to visual sensitivity (Powell et al., 2021). Participants are asked to indicate the difficulties they experience in everyday life due to dizziness on a scale from 0 (None) to 6 (Unbearable). Scores on each item can be summed to create one of three factor scores (upright posture/walking, movement, visual stimulation) and a total score. The NPQ shows good reliability (Cronbach's $\alpha = 0.91$; Yagi et al., 2019).

Visual Vertigo Analogue Scale (VVAS; Dannenbaum et al., 2011)

The VVAS is a self-report measure of visual-vertigo (visually induced dizziness) symptoms. Participants indicate the degree of dizziness they experience in 9 different situations, on an analogue scale ranging from 0 to 10. Raw scores are transformed by averaging across items and multiplying by 10, resulting in a possible score range of 0-100. The measure also shows good reliability (Cronbach's $\alpha = 0.94$; Dannenbaum et al., 2011).

Oxford-Liverpool Inventory of Feelings and Experiences (O-Life; Mason et al., 2005; Mason & Claridge, 2006)

The O-Life is a self-report measure of schizotypy, which asks participants to respond 'Yes' or 'No' to questions such as *"Would you like other people to be afraid of you?"* and *"Is it hard for you to make decisions?"*. We used the short form version of the measure's four subscales (Unusual Experiences, Cognitive Disorganisation, Introvertive Anhedonia, Impulsive Nonconformity), which all show acceptable internal consistency (Mason et al., 2005). This measure was included to assess divergent validity, the specific predictions for which are made below.

Discomfort images

To investigate the relationship between the CHYPS-v2 and reports of discomfort in response to relevant stimuli, three images were shown to participants (See *Appendix F*). Due to high contrast and spatial frequency (Penacchio et al., 2021), these images elicit discomfort in those who are sensitive to it. As the images were presented as part of the Qualtrics survey, they were rendered at differing sizes and resolutions across participants, although all participants were required to use a laptop or desktop computer to participate. We accepted this source of variability in order to recruit this large and diverse sample.

Previous studies of this nature have used numerical scales (Wilkins, 1995) (e.g., "How uncomfortable do you find this image on a scale from 0-10?") to determine discomfort. However, to minimise the extent to which results are affected by cross-participant use of scales, alternative questions were designed which aimed to differentiate response options more clearly. Participants were asked to indicate their discomfort in response to the image in two ways. The first question asked, *"Which of these statements best describes how you feel about this image?"* and was designed to better emulate everyday responses to uncomfortable stimuli. Five possible response options were provided, ranging from *"I find this image so uncomfortable I would need to look away immediately"* to *"This image is comfortable enough that I could live in a house where it had been used to wallpaper the living room"*. The second asked participants how long they would be willing to look at the image for, with response options spanning *"I immediately have to look away from this image"* to *"I could look at it for 5 minutes or more"* (See *Appendix F* for full details). These questions, and their focus on behavioural action, hoped to reduce the cross-participant variability due to differences in interpretation of scales (Hartley & Betts, 2010). Scores in response to each question were averaged across the three images.

Procedure

After signing up to participate and providing consent, participants completed all measures via Qualtrics and were compensated both upon completion of the initial study (£4.18) and additionally the CHYPS-v2 retest study (£0.75), where applicable.

Statistical Analyses

As in Study 1, Jamovi (The jamovi project, 2022) was used for descriptive analyses, bivariate correlations and the calculation of reliability measures. The psych package in RStudio (R Core Team, 2022) was used for bifactor analyses. KMO measure of sampling adequacy and Bartlett's test of sphericity both supported the use of factor analysis in this sample.

Identical model solutions to Study 1 were compared, namely: a single factor, unidimensional model, a multidimensional, correlated factors model, and a multidimensional bifactor model. Where model specification allowed, number of plausible factors was identified using parallel analysis, and alternative solutions (e.g., one few factor) evaluated (Watkins, 2018).

Fit statistics (BIC, RMSEA) were used to assess model fit, in combination with interpretability, and strength of factor and item loadings (Costello & Osborne, 2005). Macdonald's omega and Cronbach's alpha were used to assess internal consistency, where 0.70 - 0.79 is considered fair, 0.80 – 0.89 good, and > 0.90 excellent (Nunnally, 1994).

Test-retest reliability was also determined using intraclass correlation coefficients (ICC). In keeping with literature recommendations (Koo & Li, 2016; Qin et al., 2019), a two-way mixed effect model using absolute agreement was used to calculate ICC for CHYPS-v2 total and subscale scores. Values less than 0.5 are considered indicative of poor reliability, between 0.5-0.75 moderate, 0.75-0.90 good, and over 0.90 excellent (Koo & Li, 2016).

Spearman correlations were used to investigate convergent and divergent validity (de Winter et al., 2016). In these analyses, 779 participants had complete data for the MSQ, VVAS, Niigata, HADS-A, VAASP and SeSS-V. As, for ethical reasons, participants were given the option to not view the discomfort images, this was reduced to 765 for the discomfort image variables. Finally, 648 participants had complete data for the O-life subscales. Evidence for convergent validity ($r > .50$) was predicted between CHYPS-v2 and VAASP, SESS-V, Niigata, VVAS, MSQ, and discomfort image ratings. Discriminant validity, indexed by weak associations, was predicted between CHYPS-v2 and O-life subscales.

Results

Factor structure

Optimal fit was identified as the bifactor with four specific factors, interpreted as: Pattern, Strobing, Brightness, and Intense Visual Environments (IVE). In this original solution, factors consisted of 5, 8, 8, and 9 items respectively (30 items total). To create a concise and easy to administer scale, we then sequentially eliminated items according to factor loadings (e.g., items that had the lowest factor loadings were removed from each subscale). Item removal was also informed by model fit and validity parameters, as well as conceptual coverage. For instance, in circumstances where statistical indices supported the removal of several items, theoretical implications and item overlap were considered. Importantly, both model fit parameters and construct validity were not worsened by the removal of these items.

The final model is displayed in Figure 3. Each factor consisted of 5 items. The general factor was well defined; all loadings were > .45 and ECV was 0.64, supporting the presence of multidimensionality (Reise et al., 2013). RMSEA was 0.059 [90% CI 0.053 – 0.065]. Alternative

models showed comparatively poor model fit (defined by BIC and RMSEA), or poor factor loadings that were difficult to interpret.

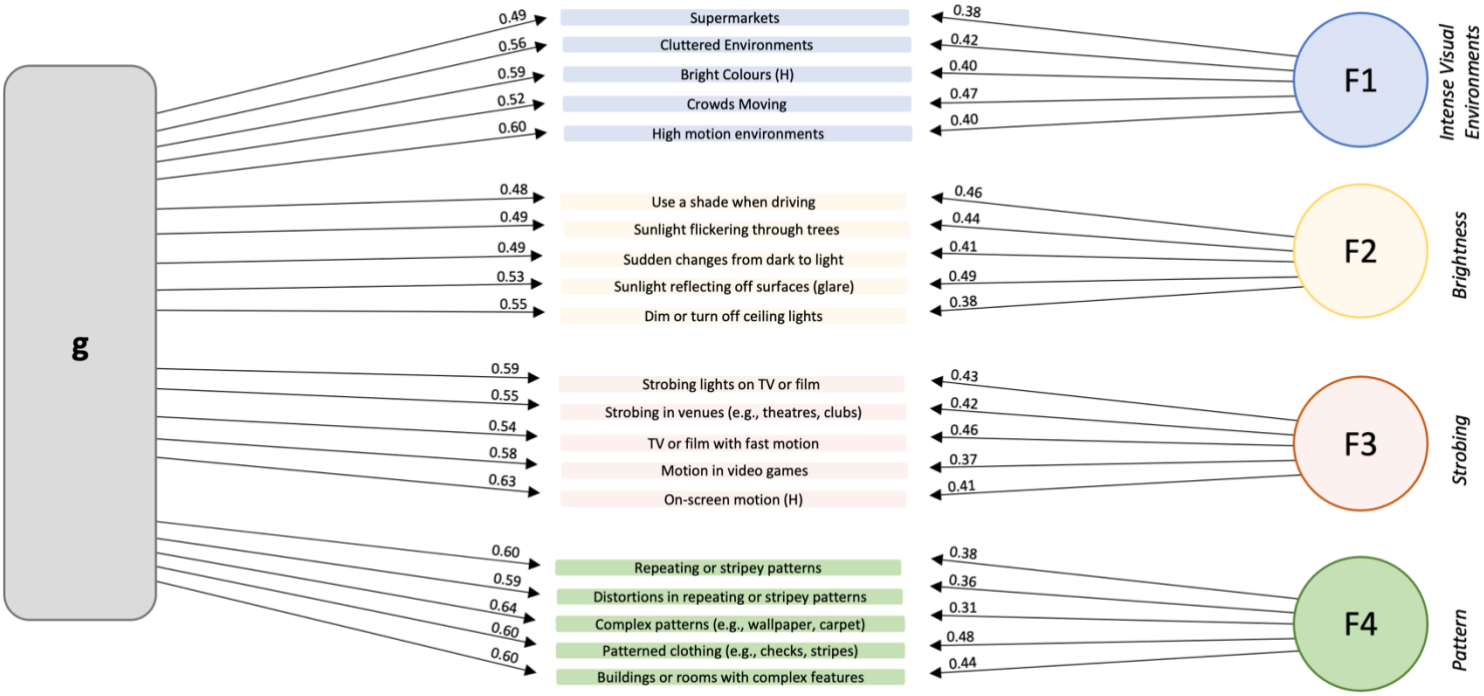


Figure 3. Final bifactor solution for CHYPS-v2. 'g' represents the general factor, F1 – F4 represent specific factors.Note that item names are simplified for ease of interpretation. The original 42 items of the CHYPS-v2 are included in Appendix E, and the final version of the measure is included in Appendix H.

Internal consistency

Internal consistency indices for total and subscale scores are displayed in Table 5. Mcdonalds' ω indicated that the general and specific factors explain 94% of the variance in the 20 items of the model. Omega hierarchical was 0.78, and the four specific factors explained 16% of the total variance in scores (0.94 – 0.78). Overall, both Mcdonalds' ω and Cronbach's *α* for the total and subscale scores indicated the measure has good internal consistency. These indices, along with the ECV, suggest that a total sum score is appropriate for this measure, however subscale scores will provide added value (Quinn, 2014; Reise et al., 2013).

Prolific sample (*n* = 790)							
Scale	**M**	**SD**	ω	***α***	**1**	**2**	**3**
Total	11.15	9.26	0.94	0.89			
(1) Strobing	2.67	3.00	0.84	0.79			
(2) Pattern	2.29	2.55	0.85	0.84	0.56		
(3) IVE	1.29	2.16	0.81	0.82	0.55	0.55	
(4) Brightness	4.89	3.49	0.80	0.77	0.54	0.57	0.55

Table 5. Summary statistics and reliability indices for CHYPS total and subscale sum scores, and associated Spearman correlations between each subscale. Note. α = Cronbach's alpha, ω = Macdonald's omega total, IVE = intense visual environments.

Test-retest reliability

Average time between the first and second administration of the CHYPS-v2 was 14.6 days (SD = 1.3, range 11.0 – 20.3). ICC for total CHYPS-v2 scores was 0.85 (95% CI 0.81 – 0.88), indicating good test-retest reliability. This was also the case for the IVE (ICC = 0.80 [95% CI 0.77-0.82]), Brightness (ICC = 0.81 [95% CI 0.79-0.88]), and Strobing (ICC = 0.83 [95% CI 0.80-0.85]) subscales. The Pattern subscale had moderate to good test-retest reliability, where ICC = 0.73 (95% CI 0.55-0.83).

Convergent and discriminant validity

Total CHYPS-v2 scores showed strong convergent validity with existing measures of visual sensitivity, the SESS-V (r_s (777) = 0.80, p < .001), and the VAASP (r_s (777) = 0.62, p < .001). Strong correlations were also present with VVAS (r_s (777) = 0.64, p < .001) and Niigata (r_s (777) = 0.59, p < .001). Moderate correlations were present between total CHYPS-v2 scores, and incidence of migraine symptoms as measured by the MSQ (r_s (777) = .46, p < .001), as well as reported comfort to discomfort images (r_s (763) = 0.53, p < .001) and time willing to look at these images (r_s (763) = 0.49, p < .001). Weak associations were found with O-life subscales Introvertive Anhedonia (r_s (646) = .24, p < .001) and Impulsive Non-conformity (r_s (646) = 0.20, p < .001). However, moderate relationships were found with the Unusual Experiences (r_s (646) = .38, p < .001) and Cognitive Disorganisation (r_s (646) = .42, p < .001) subscales. Correlations between these measures and CHYPS-v2 subscales are provided in *Appendix G.*

Discussion

We have developed a novel measure of visual sensitivity which is consistent across three samples in both its factor structure and conceptual interpretation. In Study 1, the psychometric properties of the measure's first iteration were investigated in two samples using exploratory factor analyses. The best fitting model was a correlated factors model, and included four factors (Brightness, Pattern, Strobing, IVE). Although these factor solutions were conceptually consistent across samples, specific item loadings differed, and participant feedback suggested a lack of completeness in terms of key triggers for visual sensitivity. To improve both the factor structure and construct validity of the CHYPS, question wording was modified, and 16 items added. Study 2 then used a large, demographically representative sample to evaluate the psychometric properties of the second iteration more extensively, focusing on factor structure, classical test theory scale reliability, convergent and divergent validity, and test-retest reliability. These analyses found the CHYPS-v2 to have encouraging psychometric properties.

For example, the measure again displayed a replicable, clear, and readily interpretable factor structure. A bifactor solution best fit the data in Study 2, and produced four well-defined factors (Pattern, Brightness, IVE, and Strobing, as in Study 1), with an additional, general factor representing visual sensitivity more broadly. The Pattern subscale contained items relating to aversion to or avoidance of stripey or repeating patterns, including in architecture, wallpaper, and clothing. This factor was hypothesized a priori; sensitivity to pattern is a well-documented phenomenon, both in general population (Powell et al., 2021) and specific clinical samples (e.g., migraine, Marcus & Soso, 1989; synaesthesia, Ward et al., 2017). Although this factor was not well-defined in Study 1 with only three consistent item loadings, it was bolstered by additional items included in CHYPS-v2. The Pattern subscale displayed the greatest correlation with discomfort image ratings (see *Appendix G*), where higher sum Pattern scores were associated with less willingness to look at the images, and more discomfort in response. This relationship, although moderate, might have been expected to be stronger given the content of the Pattern subscale items and the nature of images displayed. However, there are several possible explanations for this discrepancy. For example, some of the questions in the Pattern subscale relate to repeating patterns which are not stripes (e.g., checks). It is possible participants experience specific aversions, separate from the high contrast stripes found in our discomfort images. Additionally, the online nature

of the study meant discomfort images were not delivered at a consistent size, or presumably with a consistent degree of attention. These sources of variability were accepted to facilitate a large general population sample, but it is possible that the Pattern subscale would show yet stronger associations with discomfort stimuli under more controlled experimental conditions (e.g., at a consistent viewing distance).

The Brightness factor included items relating to coping mechanisms and discomfort in the presence of brightness, specifically bright overhead lighting, glare from sunlight (e.g., reflecting off water), moving from dark to light environments, and direct sunlight or sunlight through trees when driving. This factor was similarly hypothesized based on existing work as sensitivity to light is commonly reported (Digre & Brennan, 2012; Wilkins et al., 2021). However, the Brightness factor also highlights the important role participant feedback played in the development of the CHYPS, as items such as discomfort from glare were derived from participant feedback. This is a strength of the measure, as we have created items which are both theoretically relevant and represent individual experience.

A motion factor was hypothesized consisting of items relating to discomfort in response to large scale movements (e.g., crowds moving) and fast-paced movement on a screen (e.g., video games, action films). Instead, motion items were split across Strobing and IVE factors. Although not predicted, the separation of items was still highly interpretable. Motion items that loaded onto the IVE factor related to large-scale, real-life movements such as watching fast-paced sports or crowds moving. The remaining items on the IVE scale measured discomfort in supermarkets and colourful or cluttered environments, suggesting this factor broadly represents visual sensitivity in the presence of complex visual stimulation. The role of complex, urban stimuli and colour in visual sensitivity has been reported previously (Le et al., 2017; O'Hare et al., 2023). The IVE factor also bears striking consistency with the dizziness triggers of neuro-vestibular disorder PPPD (Popkirov et al., 2018), which include supermarket aisles and busy moving traffic. Indeed, recent work finds PPPD symptoms to be relatively common in the general population, which may contribute to the emergence of this factor (Powell et al., 2020a). The magnitude of correlation between the IVE subscale and VVAS and Niiigata scores, which measure PPPD symptoms (See *Appendix G*), also supports this association and provides evidence of convergent and construct validity for this measure. It would be of interest for future work to investigate the pattern of responding on the CHYPS in

individuals diagnosed with PPPD, to ensure the measure does not display any differential item functioning across varying levels of visual sensitivity in clinical groups.

The remaining motion items which did not load on the IVE factor assessed discomfort in response to screen-based motion, such as fast movements in action films and video games. These items instead formed part of the Strobing factor, along with dislike of strobing or flashing lights (either in venues such as theatres, or in films or TV). Close inspection of items contributing to this subscale suggested that this grouping was not simply an artefact of wording or structure but appeared to reflect a tendency for individuals sensitive to strobing light to concurrently be sensitive to screen-based motion. This tendency could be driven by perceptual similarities between these visual sensitivity triggers. For example, action films and video games often include rapidly changing scenes which can contain high contrast or flashing imagery (e.g., gunfire). Similarly, these forms of media also include camera motion such as panning, roll, shaking, and zoom, known to elicit headache, discomfort, and motion sickness in some individuals (Kuze & Ukai, 2008; Ujike et al., 2008). It may be that these types of on-screen motion, which likely involve fast changes in colour, brightness, and pattern, elicit similar perceptual and metabolic effects as strobing or flickering lights (Harding & Harding, 1999; Honey & Valiante, 2017), contributing to the association between these items. Associations between flickering lights and on screen motion are also present in photosensitive epilepsy, where seizures can be elicited by motion in films, video games, and social media (Fisher et al., 2022; Harding & Harding, 1999) as well as strobing lights (Fisher et al., 2022). Mechanisms underlying discomfort in response to these stimuli (E.g., gamma oscillations; Hermes et al., 2017; Yoshimoto et al., 2017) may therefore involve more comparable pathways when compared to other forms of discomfort, giving rise to the Strobing factor found here. However, this is speculative at this stage and would require further investigation.

It should also be noted that the CHYPS items relating to on-screen motion do not necessarily specify the specific forms of movement that are uncomfortable. For example, participants were asked about avoidance of films or TV which use “lots of fast movements or shaky camera footage”. It is possible that participants interpreted this question differently, some assuming this referred to rapid scene changes, whilst others assume it refers to the movement of individuals or objects in a scene. Ultimately, this is not problematic in terms of this study’s findings as the item remains specific to on-screen motion regardless of interpretation. However, responses to different forms of on-screen motion, and possible

protective guidance for consumers or creators (Prasad et al., 2012), would be an interesting avenue for future research.

The findings from our bifactor model suggest that the CHYPS can also be conceptualised using a total sum score which represents a general visual sensitivity factor, which shows good test re-test reliability. As was the case with the measure's subscales, the CHYPS total similarly showed favourable associations with other relevant measures. Strong correlations were found with existing questionnaire measures of visual sensitivity, the SeSS-V and VAASP, providing evidence of convergent validity. Stronger relationships were observed with the SeSS-V, likely as this measure adopted a similar ethos to the CHYPS of focusing on functional rather than affective responses to stimuli. Comparatively lower, albeit still moderate, relationships were found with total scores and measures of interest including the MSQ and discomfort images. Migraine is known to co-occur with visual sensitivity (Huang et al., 2003; Wilkins et al., 2021), and thus would be expected to associate with CHYPS scores in such a way.

Divergent validity was assessed using correlations with the O-Life, a self-report measure of schizotypy. This measure was chosen to ensure that high scores on the CHYPS are not simply reflective of a tendency to respond positively on questionnaire measures. However, given that subjective sensory sensitivity (including in the visual domain) is heightened in schizophrenia (Zengin & Huri, 2022), a small relationship would be anticipated. This was found for the Impulsive Nonconformity and Introvertive Anhedonia subscales which assess lack of physical or social enjoyment, and impulsive forms of behaviour respectively. However, the Unusual Experiences subscale showed greater correlation with the CHYPS total and subscale scores. Given specific relationships between unusual experiences and subjective sensory sensitivities have been reported previously (Horder et al., 2014), and both are associated with elevated cortical hyperexcitability (Braithwaite, Broglia, Bagshaw, et al., 2013), this is perhaps unsurprising. Moderate correlation was also found with the Cognitive Disorganisation subscale, which assesses constructs such as poor attention, concentration, and decision making. Considering this subscale's items more closely, it is possible these relationships are driven by overlapping variance caused by the effects of visual sensitivities. For instance, the Cognitive Disorganisation items include *"Are you easily confused if too much happens at the same time?"* and *"Are you easily distracted when you read or talk to someone?"*. Distractibility as a result of subjective sensory sensitivities is a common consequence, documented in

existing measures (Brown & Dunn, 2002), and may therefore account for the association between this subscale and visual sensitivity found here.

Overall, factor analytic work in Studies 1 and 2 indicated that visual sensitivity is not necessarily a unidimensional construct as has been previously reported (Aykan, Vatansever, & Doğanay-erdoğan, 2020). Instead, there appear to be four consistent and replicable factors upon which people can vary (Pattern, Strobing, Brightness, and IVE). These factors had good reliability, align with existing theory, and show expected relationships both with existing sensitivity measures and clinically relevant constructs (e.g., migraine, PPPD).

Implications and Limitations

The emergence of these factors may be useful in future work investigating mechanisms of visual sensitivity. For example, hyperexcitability of the visual cortex has been posited as causal in the experience of sensitivity to flicker (Yoshimoto et al., 2017), pattern (Wilkins, 1995), colour (O'Hare, 2017), motion (Fisher et al., 2022), and complex environments (Le et al., 2017). However, it is not yet clear to what extent these mechanisms are similar or different. For example, what differences in neural architecture, cognition, or cortical response might lead an individual to be highly visually sensitive to pattern, but not to light?

It is possible that individual differences in visual sensitivity arise from differing solutions to the balancing act between information gathering and the use of metabolic energy carried out by the perceptual system. The aim is to minimize the metabolic energy in responding to a stimulus, whilst maintaining optimal detection and discrimination of signals. Under the theory of inefficient coding, neural representations of stimuli that are frequently experienced (e.g., natural scenes) are therefore predictably sparse based upon their statistical properties, to prevent metabolic cost (Olshausen & Field, 1996). In contrast, stimuli which deviate from commonly encountered environments elicit a greater neural response (Juricevic et al., 2010; Le et al., 2017). Individual differences in visual sensitivity may therefore be a manifestation of differing solutions to this same underlying balancing act between information and energy. A differential pattern of visual sensitivity (e.g., to pattern, but not to light) may arise for one such solution but not another, for example. This is speculative at this stage, and the tendency for those with specific diagnoses to a adopt a solution which results in such marked increases in visual sensitivity would require explanation. However, it is hoped that the CHYPS and its associated subscales will provide a basis from which future research

can investigate these questions with more specificity. Further consideration of the causes of factors of visual sensitivity is provided in the General Discussion.

Alongside establishing that visual sensitivity is not necessarily a unidimensional construct, this work provides additional insights that are somewhat at odds with existing research. One notable difference is the experience of discomfort when reading. Previous literature has framed text as a form of striped stimulus, where the text itself (minus ascenders and descenders) is perceived similarly to the black bar of a grating, with between-text gaps acting as contrast. Discomfort when reading has therefore been allied with aversion to pattern, and visual sensitivity more generally. Items relating to discomfort in response to text were therefore included in both initial iterations of the CHYPS, with the hypothesis that these would load with the Pattern factor. However, these items were not retained in any of the factor solutions and are therefore not part of the final measure (available in *Appendix H*). The absence of reading related questions, and indeed the multidimensional nature of the CHYPS, directly contrasts measures such as the Visual Discomfort Scale (VDS; Conlon et al., 1999), which assesses aversion to pattern, reading, and lights. This measure's dimensionality appears to be under debate; despite being conceptualised as unidimensional during its development, subsequent work instead reports a three-factor solution, where one factor contains all items relating to lighting and pattern (Borsting et al., 2007). Almost all remaining reading related questions loaded elsewhere, suggesting a dissociation between reading and pattern discomfort that is consistent with the findings reported here. Different aetiologies of visual sensitivity may drive these discrepant findings (i.e., cortical hyperexcitability; Wilkins, 1995) versus or in combination with accommodative or binocular disorder which can co-occur with reading delay and distortion (Borsting et al., 2007; Della Sala & Anderson, 2012), but our results do suggest that discomfort when reading and visual sensitivity more generally are separable constructs.

Important limitations in this work should also be considered. In particular, possible implications of our sampling technique. Although the sample were representative of the UK in terms of sex, ethnicity, and age, they may differ from the general population in relevant ways. For example, participating in online research of this kind would require a certain level of digital literacy (Munger et al., 2021), as well as time and resources, contributing to a possible self-selection bias. It is also possible that people willing and able to participate in Prolific studies are unlikely to be individuals with high visual sensitivity, given it requires

extended exposure to digital screens. However, although the CHYPS scores are negatively skewed, we did not find that there was a lack of high scoring participants in our sample (scores ranged from 0-53). Nonetheless, it would be important to investigate the distribution of scores in a general population sample, using alternative methods (e.g., physical rather than screen-based measures). This could also contribute to estimations of occurrence of subjective sensory sensitivity, the understanding of which is currently limited outside of clinical groups (e.g., autism; Leekam et al., 2007), which presents a challenge when establishing clinically (or functionally) significant cut offs.

There is also a need to extend this work to a confirmatory sample. Exploratory factor analyses were used in the initial development whilst factor structure and items were still being investigated, in line with literature recommendations (Watkins, 2018; Yong & Pearce, 2013). However, with replicable and clear factor structure now established, a confirmatory factor analytic approach in another large, general population sample is required to finalise the CHYPS. This large sample would also allow for additional explorations of the validity of the measure, including convergent and divergent validities.

Summary

In summary, this work presents a novel self-report measure of visual sensitivity which shows promising psychometric properties, including construct, convergent, and test-retest reliability. The measure also displays a highly consistent factor structure, at odds with existing measures which suggest the latent construct of visual sensitivity to be unidimensional. Instead, we find sensitivity to Pattern, Strobing, IVE, and Brightness, to be distinct factors alongside a strong general factor. These factors represent a useful avenue for future research to investigate causes and correlates of visual sensitivity with greater specificity and understand what may give rise to differential patterns of reactivity to visual stimuli. A confirmatory sample is required however to finalise the factor structure, validity, and scoring of the CHYPS, before additional work is undertaken.

Chapter 6: Confirming the psychometric properties of the CHYPS-V in a large community sample

Introduction

In Chapter 5, the development of the visual Cardiff Hypersensitivity Scale (CHYPS-V) was described. The CHYPS-V is a novel, self-report measure of subjective visual sensitivities. Specific advantages of the scale when compared to existing measures include its focus upon functional impact (rather than affective change), its integration of participant feedback throughout development, and its identification of psychometrically sound factors of visual sensitivity.

Existing questionnaires assessing visual sensitivities had not explored the possibility of subtypes of the experience. However, across four samples, the CHYPS-V showed a highly replicable four factor solution. The four identified factors of visual sensitivity included Intense Visual Environments (supermarkets, cluttered or high motion spaces), Brightness (overhead lighting, sunlight, glare), Strobing (flashing lights in theatres, motion on screens) and Pattern (complex wallpapers, architecture, stripes). An additional general factor of visual sensitivity was also identified using an exploratory bifactor approach, supporting the use of both total and subscale scores for the measure. However, in line with literature recommendations (Yong & Pearce, 2013), a confirmatory analysis is recommended to validate the factorial structure of the CHYPS-V. The present study therefore aims to verify the four factors of visual sensitivity in a large, confirmatory sample.

Samples thus far (see Chapter 5) have included undergraduate Psychology cohorts and participants from the online research platform Prolific. Whilst the former were predominantly young females, samples taken from Prolific were stratified across key variables (age, sex, ethnicity) to be representative of the United Kingdom's demographics (as identified by the UK Office of National Statistics). Although these samples are representative according to these variables, self-selection biases are likely relevant. Use of alternative samples, with different methods of recruitment, would therefore be beneficial in further ensuring the CHYPS-V shows consistent factor structure across populations.

Participants in the present study were therefore recruited from a community health list (HealthWise Wales) in Wales, which differs from Prolific in several important ways. Prolific users likely include participants who are highly experienced in taking surveys (Douglas et al., 2023), which has implications for our measure. For instance, a person who is willing and able

to take hundreds of surveys per year (as is common on Prolific, Douglas et al., 2023) may be less likely to experience screen-based visual sensitivities (e.g., aversion to scrolling or to high-contrast text or pattern). HealthWise Wales participants would still need to be able to look at a screen comfortably for periods of time, however as they are not compensated this is likely to be comparatively less frequent than Prolific users. Instead, the central advertised incentive to participate in HealthWise Wales studies is to improve health research in Wales. The HeathWise Wales cohort also require less digital literacy, as the survey link is directly emailed, and the participants are older when compared to Prolific users (e.g., Douglas et al., 2023; Hurt et al., 2019). Self-selection biases are therefore still relevant in this group, but differ in kind from Prolific participants.

This cohort therefore represents an opportunity to assess the psychometric properties of the CHYPS-V in a sample whose demographic variables and recruitment practice differs from those used previously (i.e., Prolific, undergraduate students). Confirmatory bifactor analyses will therefore be used to assess whether the four-factor solution described in Chapter 5 is consistent in this sample.

Methods

Participants

Participants in a community health list in Wales were emailed with an advert and link to participate in a survey; all materials were provided in English and in Welsh. The advert described the survey as investigating why some people experience visual sensitivities and others do not, and how this relates to other everyday experiences. The following text was included to emphasise the inclusivity of the study and help to prevent self-selection biases: *"Everyone has a different sensory experience of the world, and therefore all HealthWise Wales participants over the age of 18 are welcome and encouraged to participate".*

The survey link was sent via email and 1511 responses were received. Exclusion criteria were then applied based on a comprehension check, an attention check, implausible clinical diagnosis responses and incomplete responses. A comprehension check is included at the beginning of the CHYPS-V, which specifies what is meant when the term 'uncomfortable' is used throughout the measure (relating to concerns that this may be incorrectly interpreted as disgusting, upsetting, or frightening). Participants are provided with two opportunities to provide the correct answer to the question: *"Please indicate what we mean by*

'uncomfortable' in the questions you are about to answer", which would be: *"Physical pain, tiredness or strain in or around your eyes or head".* In this sample, 257 did not complete the survey, 34 participants did not provide a correct answer to the comprehension question, and a further 61 participants responded incorrectly to an attention check, which asked them to select "Strongly Agree" in response to an item.

Participants were asked to indicate self-identification with, or receipt of, a clinical diagnosis of a variety of conditions and areas of neurodiversity, with additional space provided to indicate any other diagnoses. Details of reported diagnoses are provided in *Appendix A*.

Seven participants reported receiving a diagnosis of every one of the 21 listed diagnoses. As these participants may not have been fully engaging with the survey, or interpreting questions incorrectly, their data was removed. Complete data is also required for bifactor modelling, and incomplete responses on the CHYPS measure were therefore also removed. The final sample used for all analyses, to allow for comparability, consisted of 1133 participants.

The mean age of the final sample was 62.8 (SD = 13.5, range 18-93) and 39% identified as male. A further 58.2% identified as female, and 0.9% self-identified as with another gender identity. Four individuals stated they would prefer not to indicate their gender, and 46 participants did not provide their age.

Measures

Cardiff Hypersensitivity Scale – Visual (CHYPS-V)

As described in Chapter 5, the CHYPS-V is a 20-item measure designed to assess subjective visual sensitivities. As part of the instructions, the meaning of 'uncomfortable' in the context of visual sensitivities is described (See *Appendix H*) as well as the following statement: *"Please answer each question based on what happens when you experience a given situation, rather than how often you experience it. For example, if you always experience discomfort when ironing a stripey shirt, but don't often iron them, you should respond 'Almost Always'"*. This instruction was included based on participant feedback from previous versions of the CHYPS-V. Participants respond to each item on a four-point Likert scale, ranging from "Almost Never" to "Almost Always".

Information on age, self-reported gender, and clinical diagnoses and/or areas of neurodiversity were collected. Alongside this participants completed additional quantitative

measures which are reported in Chapter 7, as this chapter focusses only on the confirmatory analysis of the CHYPS-V. All measures were delivered via Qualtrics survey. Participants were not compensated for their participation.

Statistical analyses

A confirmatory bifactor model was tested which included a general visual sensitivity factor, and a further four specific factors: Intense Visual Environments, Brightness, Strobing, and Pattern, prespecified based on the results of exploratory bifactor analyses reported in Chapter 5.

Jamovi (The jamovi project, 2022) was used for descriptive analyses, and to calculate Spearman correlations between CHYPS-V subscales (de Winter et al., 2016). The lavaan (Wahren, 2012) package was used in RStudio (R Core Team, 2022) for bifactor modelling. Macdonald's ω is reported as an indicator of internal consistency, as it is argued to provide a less biased estimate than Cronbach's α (Dunn et al., 2014, acceptable ω > .70; Ponterotto & Ruckdeschel, 2007). However, alpha is also reported for completeness, where 0.70 - 0.79 is considered fair, 0.80 – 0.89 good, and > 0.90 excellent (Nunnally, 1994).

The confirmatory bifactor model used diagonally weighted least squares (DWLS) estimation (Savalei & Rhemtulla, 2013). As is classically recommended, the following goodness-of-fit measures were calculated: Comparative Fit Index (CFI) > .95, Root Mean Square Error of Approximation (RMSEA) < .06, and Standardized Root Mean Square Residuals (SRMR) < .08 (Hu & Bentler, 1999). However, adjustments to traditional fit indices for confirmatory models are increasingly recommended in the literature. For example, x^2/df (with optimal fit < 5) is proposed as an improvement over chi-square statistics which can be affected by sample sizes (Alavi et al., 2020). Similarly, SRMR/R^2 where < .05 indicates good model fit, as recommended by Shi et al. (2018) has recently been found to be beneficial in identifying mis-specified confirmatory bifactor models (Ximénez et al., 2022), particularly in the context of limiting cross loadings as is the case in the *lavaan* factor model.

For completeness, both classical (CFI, RMSEA, SRMR) and adjusted (x^2/df, SRMR/R^2) fit indices will be reported and were used to evaluate the model. However, as bifactor models risk overfitting (Bonifay et al., 2017b; Greene et al., 2019; Markon, 2019), and due to concerns around these fit statistics when using DWLS estimation (Xia & Yang, 2019), interpretability, parsimony, and theoretical implications were also important in appraising the model.

Results

Confirmatory bifactor model showed good fit statistics, CFI = 0.96, TLI = 0.95, SRMR = 0.02, aside from chi square (χ^2 (150) = 544.57, p < .001) and borderline RMSEA = 0.08 [90% CI 0.07 – 0.09]. Adjusted fit indices were also acceptable: x^2/df = 3.63, SRMR/R^2 = 0.03.

Factor loadings are displayed in Table 2. All items loaded significantly on the general factor, and their respective specific factors, with the exception of the Colour item (*"When there are lots of bright colours around me, I tend to get a headache")*.

Item	G	IVE	Brightness	Strobing	Pattern
Supermarkets	0.82*	0.31*			
Cluttered environments	0.76*	0.35*			
Bright colours (H)	0.89*	0.03			
Crowds moving	0.85*	0.38*			
High motion environments	0.91*	0.12*			
Use a shade when driving	0.63*		0.55*		
Sunlight flickering through trees	0.72*		0.28*		
Sudden changes from dark to light	0.74*		0.22*		
Sunlight reflecting off surfaces (glare)	0.73*		0.38*		
Dim or turn off ceiling lights	0.74*		0.21*		
Strobing lights on TV or film	0.71*			0.46*	
Strobing in venues (e.g., theatres, clubs)	0.70*			0.50*	
TV or film with fast motion	0.78*			0.28*	
Motion in video games	0.80*			0.26*	
On-screen motion (H)	0.88*			0.25*	
Repeating or stripey patterns	0.78*				0.41*
Distortions in repeating or stripey patterns	0.75*				0.39*
Complex patterns (e.g., wallpaper, carpet)	0.85*				0.37*
Patterned clothing (e.g., checks, stripes)	0.80*				0.47*
Buildings or rooms with complex features	0.85*				0.38*

Table 2. Confirmatory bifactor model of the CHYPS-V (n = 1133). *Note*: item names are approximations of the complete CHYPS-V items which can be found in *Appendix H. (H) indicates that the item asked whether the stimuli triggered a headache.* IVE = intense visual environments. *p < .005

Descriptive statistics for the total CHYPS-V and subscale scores are shown in Table 3, along with measures of internal consistency for total and subscale scores. Both the total CHYPS-V and Pattern subscale score showed excellent internal consistency, whilst Strobing, IVE, and Brightness subscales showed good internal consistency. Subscale scores showed strong correlations with each other.

Scale	M (SD)	α	ω	1	2	3
Total	12.63 (11.84)	0.95	0.95			
1. IVE	1.48 (2.60)	0.87	0.88			
2. Brightness	5.37 (3.95)	0.85	0.85	0.62		
3. Strobing	3.25 (3.64)	0.87	0.88	0.64	0.68	
4. Pattern	2.55 (3.28)	0.91	0.91	0.62	0.64	0.59

Table 3. Summary statistics and reliability indices for total and subscale CHYPS-V scores, and associated Pearson's correlations between subscales. Note. α = Cronbach's alpha, ω = Macdonald's omega total, IVE = intense visual environments. The final three columns show Spearman correlations between subscores.

Discussion

Overview of findings

This study sought to confirm the psychometric properties of the CHYPS-V in a large community sample with very different demographics and recruitment biases compared to the samples in Chapter 5. Chapter 5 described the development of the CHYPS-V and the identification of its latent structure. A psychometrically strong bifactor model, including one general factor along with the four specific factors identified was identified. Using this bifactor solution, the current analysis sought to use confirmatory bifactor modelling to assess the dimensionality of the CHYPS-V in a large, general population sample.

A confirmatory bifactor model was supported, with almost all items significantly loading on their hypothesized specific factors, and all items displayed significant loading on the general factor, supporting the bifactor structure of the CHYPS-V. As the model reduces small cross loadings to zero, the fit of this confirmatory analysis also supports the use of sum scoring for the measure (Frazier et al., 2022). The internal consistency of the total and subscale scores were also either good or excellent, according to established standards (Nunnally, 1994, Ponterotto & Ruckdeschel, 2007). Across a total of four samples therefore, the CHYPS-V shows reliable evidence of strong internal consistency.

Limitations

Limitations in the bifactor model fit should be highlighted. Fit statistics including CFI, TLI, and SRMR (and adjusted SRMR) were all acceptable. The chi squared test of model fit was significant and would thus classically suggest poor model fit. However, recent work emphasizes the role of sample size in interpreting chi-square; specifically, larger sample sizes (as is the case here) are known to reduce the p-value, even when model misfit is limited (Alavi

et al., 2020). Using an alternative approach, integrating degrees of freedom the chi square statistic (x^2/df), results in acceptable fit. The RMSEA value for the model was also only bordering on acceptable. However, there is a need to consider fit indices in a holistic manner, not relying on one particular indicator to provide a binary decision on model acceptability (Alavi et al., 2020). Similarly, as bifactor models have a tendency to overfit data, caution should be used when interpreting fit indices (Bonifay et al., 2017b) and both theory and parsimony should be also considered. Contextual and theoretical factors, including the replicated factor structure of the CHYPS-V in Chapter 5, also support the current bifactor model.

Additional limitations include one item showing non-significant loading on its hypothesized specific factor. The CHYPS-V item relating to visual sensitivity to colours loaded significantly on the general factor but did not significantly load on the Intense Visual Environments factor. It is possible this is due to the differing restrictions of a confirmatory bifactor model, which constrains cross-loadings to zero. This statistical restriction is not expected to be problematic to the model itself; the sample size is large, previous data indicates that cross loadings are small and thus less consequential (Ximénez et al., 2022), and SRMR correction (which shows specific efficacy in detecting problems in model identification due to ignoring cross-loadings; Ximénez et al., 2022) did not indicate model misspecification. However, it is possible that this restriction had specific effects on the colour item, leading to low IVE factor loading.

Despite this, there is justification for retaining the item in the measure. The content of this item was taken from feedback during the CHYPS-V's development, where participants indicated that experiences of sensitivity to bright or contrasting colours were absent from earlier iterations of the measure. This insight from participant experience, the survival of the item in the final bifactor model reported in Chapter 5, and the item's clear relevance to the general visual sensitivity factor reported here (factor loading = 0.89) indicates the item's importance, and thus supports its inclusion in the final measure. However, it will be important for future work using the CHYPS-V to further establish the status of the item in other samples.

Other items also showed reduced, but not non-significant loadings on the present bifactor solution when compared to previous iterations described in Chapter 5. For example, the factor loading of the item assessing sensitivity to bright lighting is much reduced. There is the potential for loadings on the general factor to be increased whilst specific factor loadings are reduced in bifactor models of this kind, which may explain this discrepancy (Ximénez et

al., 2022). This difference may also be influenced by the nature of the sample, who were predominantly older adults (mean age = 62.8). This difference may affect item loading in several ways; for instance, a reduced loading on items relating to motion associated with video games might reflect a reduced tendency for older adults to engage with video games and thus experience this form of sensitivity. There is also evidence to suggest age-related decline in visual sensitivities (Evans & Stevenson, 2008; Kelman, 2006; Qi et al., 2019) which could underlie these effects. The tendency for certain items (e.g., high motion environments, brightness) to be particularly affected would require explanation however, and further investigation in similar samples would be beneficial.

Summary

In summary, the present study supports the previously described four factors of visual sensitivity. The factor structure of the CHYPS-V has now been demonstrated across a total of four samples, including over 2700 participants, using three different recruitment strategies. The four factors of visual sensitivity are therefore highly consistent and psychometrically sound. Future research will benefit both from being able to assess these factors, and from the general visual hypersensitivity measured by CHYPS-V, which is more complete and statistically robust than provided by previous questionnaires.

Chapter 7: The occurrence of factors of visual sensitivity across diagnoses and areas of neurodiversity, and their association with specific symptoms of anxiety

Introduction

As described in the General Introduction, many clinical diagnoses are found to associate with differences in subjective visual sensitivity. For instance, individuals with autism (Zeisel et al., 2023), ADHD (Kamath et al., 2020), and migraine (see Chapter 2) commonly show increased visual sensitivity in questionnaire measures. Visual sensitivity in other diagnoses and areas of neurodiversity are also increasingly investigated; for instance, increased subjective visual sensitivity is found in individuals with depression (Hui et al., 2022; Qi et al., 2019), Tourette's syndrome (Ludlow & Wilkins, 2016), PPPD (Powell et al., 2020b), OCD (Lewin et al., 2015), and fibromyalgia (Wilbarger & Cook, 2011).

Although suggesting that sensitivities are broadly increased, measures used in extant work do not consider subtypes of visual hypersensitivity. As described in Chapters 5 and 6, visual sensitivities do not appear to be unidimensional in nature, but instead can be conceptualised into subtypes of sensitivity to intense visual environments, brightness, strobing, and pattern. When describing visual sensitivities as increased in clinical diagnoses therefore, it is yet to be determined whether this is consistent across visual sensitivity factors. For instance, the Glasgow Sensory Questionnaire's (Robertson & Simmons, 2018) visual hypersensitivity subscale consists of three items which focus on bright or flickering lights and noticing small particles in the air. A high score on this subscale (e.g., as reported in autism; Zeisel et al., 2023) therefore does not provide evidence of sensitivity to repeating patterns for example. Similarly, the Adolescent/Adult Sensory Profile (Brown & Dunn, 2002) does not include questions relating to flicker or screen-based motion, as measured by the Strobing factor defined in Chapter 5. Thus, the specific nature of visual sensitivity across different clinical diagnoses is undetermined. Enhancing understanding of how patterns of subjective visual sensitivity might differ across diagnoses, both in terms of magnitude and quality, has implications for underlying mechanisms and implementation of appropriate adaptations where needed (Weber et al., 2022).

This chapter therefore uses the newly developed CHYPS-V to investigate visual sensitivities across a range of clinical diagnoses and areas of neurodiversity. Additionally, given comorbid diagnoses are common (e.g., Smitherman et al., 2013; Spinhoven et al., 2014; Swinbourne & Touyz, 2007), there is a need to consider how co-occurring diagnoses might

influence our understanding of visual sensitivities. Regression analyses will therefore be used to statistically control for co-occurring conditions.

Part two of this chapter will also provide specific consideration to the association between visual sensitivities and anxiety. As discussed and examined in Chapters 2, 3, and 4, anxiety is known to correlate with sensory sensitivities both at symptom (Engel-Yeger & Dunn, 2011b) and diagnosis (Isaacs et al., 2020; Lewin et al., 2015) level. Despite this relationship being reliably shown, our understanding of the causal mechanisms that give rise to this consistent finding is limited. As described in the General Introduction, explanations are both unidirectional and bidirectional in nature, spanning from descriptive accounts based in conditioning (Green & Ben-Sasson, 2010), to neural underpinnings (Schwarzlose et al., 2023; Shin & Liberzon, 2010), and contextual or diagnostic overlap (Green & Ben-Sasson, 2010). However, existing investigations have tended to focus on anxiety symptoms as a single construct.

For instance, quadrants of the AASP have been found to positively associate with sum scores of questionnaire measures of anxiety (Engel-Yeger & Dunn, 2011b; Levit-Binnun et al., 2014). The use of sum scores is consistent with a common cause (or reflective; Schmittmann et al., 2013) model in clinical psychology, whereby diagnoses are constructs which cause observable symptoms; for instance, anxiety as an entity causes the symptoms of excessive worry and feeling of panic. This use of sum scores assumes that items or indicators are equivalent in representing the underlying condition, and thus a sum score adequately represents the construct.

Recent work has instead described a move towards a causal systems perspective (Borsboom, 2008). This approach instead considers diagnoses to constitute of co-occurring symptoms which causally influence each other, rather than stemming from an individual cause. This is consistent with work finding dissociable relationships amongst symptoms (e.g., less sleep as causal in the development of anxiety symptoms; Neckelmann et al., 2007) and idiographic symptom networks in individuals with GAD (Fisher et al., 2017) and between symptoms and precipitating factors (e.g., in depression; Tennant, 2002). This approach has been acknowledged as important in understanding, with greater specificity, the cause and maintenance of diagnoses such as anxiety and depression (Fried & Nesse, 2015b, 2015a), and indeed how they relate to other experiences.

The network approach to psychopathology allows investigation of these interacting symptoms or experiences via network models. Network models provide visual and statistical understanding of how symptoms associate with each other; when a symptom central to a network is experienced ('activated'), it activates other, nearby symptoms. A symptom central to a given network is therefore more likely to influence other symptoms than one that is peripheral. Network models also allow for the investigation of how different groups of symptoms might associate with each other; for instance, which symptoms are important in connecting them (Beard et al., 2016).

This approach was therefore adopted in part two of this chapter. Previous work investigating associations between anxiety and sensory sensitivities has relied on sum scores, which restricts understanding of how the two phenomena relate to a broad, singular concept of anxiety, which itself can be heterogenous (Fisher et al., 2017). Instead, specific symptoms of anxiety will be included in a network analysis to investigate associations with factors of visual sensitivity (as defined by the CHYPS-V), as well as migraine and visually-induced dizziness (known correlates described in Chapters 2 and 5). The presence of communities (clusters) of symptoms will also be investigated, as well as the role of specific symptoms in associations within and between these, with a view to beginning to unpack why associations between anxiety and visual sensitivities exist.

Methods

Participants

The participant sample consisted of two cohorts:

1. Paid participants (n = 770)

   These participants are a subset of those recruited in Chapter 5 using the online research platform Prolific (https://prolific.co/; see Chapter 5 Methods). A further 20 participants were removed from this sample for incomplete data on measures on interest (CHYPS-V, HADS-A, age, gender). Due to a lack of power to detect between group differences, those self-reporting their gender as 'Other' or 'Prefer not to say' were also not included in these analyses.

2. Health Wise Wales (n = 1071)

   These participants are a subset of those recruited in Chapter 6 using a community health list in Wales (see Chapter 6 *Methods*). Participants who did not provide complete data for all variables of interest (CHYPS-V, HADS-A, age, gender) were removed, resulting in a final sample of 1071. Due to a lack of power to detect between group differences, those self-reporting their gender as 'Other' or 'Prefer not to say' were also not included in these analyses.

Demographic data for each cohort, and the total sample (n = 1841) is displayed in Table 1.

Cohort	**Mean Age (SD)**	**Age Range**	**Male**	**Female**
Prolific (n = 770)	45.8 (15.6)	18-88	49.0	51.0
Health Wise Wales (n = 1071)	70.0 (13.3)	18-93	40.1	59.9
TOTAL	55.8 (16.6)	18-93	43.8	56.2

Table 1. Demographic data for each participant cohort and the total participant sample.

Measures

Cardiff Hypersensitivity Scale – Visual (CHYPS-V)

As described in Chapters 5 and 6, the CHYPS-V's final iteration consists of 20 items. Participants respond with the frequency with which each item is experienced, on a four-point Likert scale from "Almost Never" to "Almost Always". To improve consistency and clarity, the questionnaire's instructions include a description of what is meant by the term

'uncomfortable' throughout the measure, followed by a comprehension question *('Please indicate what we mean by 'uncomfortable' in the questions you are about to answer:').* A total CHYPS-V score can be calculated, as well as four subscale scores (Intense visual environments (IVE), Brightness, Strobing, and Pattern). The complete CHYPS-V is provided in *Appendix H*.

Self-report diagnoses

Participants were asked to indicate whether they had received a diagnosis or self-identified with a range of clinical diagnoses or areas of neurodiversity. Space was also provided to indicate conditions not pre-specified.

Migraine Screening Questionnaire (MS-Q; Láinez et al., 2005)

The MS-Q includes five items which ask individuals about migraine episodes experienced in their lifetime, each with a yes (1) or no (0) response. Example items include "Do you usually suffer from nausea when you have a headache?" and "Does light or noise bother you when you have a headache?". Items are summed to create a total MSQ score. The MS-Q shows adequate and internal consistency (Cronbach's $\alpha = 0.82$; Láinez et al., 2005).

Visual Vertigo Analogue Scale (VVAS; Dannenbaum et al., 2011)

The VVAS is a self-report measure of visual vertigo (visually-induced dizziness) symptoms. Participants indicate the degree of dizziness they experience in nine different situations (e.g., going on escalators, watching television), on an analogue scale ranging from 0 to 10. Raw scores are transformed by averaging across items and multiplying by 10, resulting in a possible score range of 0-100. The measure also shows good internal consistency (Cronbach's $\alpha = 0.94$; Dannenbaum et al., 2011).

Hospital Anxiety and Depression Scale (HADS; Zigmond & Snaith, 1983)

The HADS is a 14-item measure assessing generalized symptoms of depression and anxiety. Participants are asked to indicate the frequency they experience each item, on a four-point scale (e.g., where 0 = Not at all, 1 = Occasionally, 2 = A lot of the time, 3 = Most of the time). The depression (HADS-D) and anxiety (HADS-A) subscales are calculated by summing their seven corresponding items; for the purpose of the current analyses, only the 7-item anxiety subscale was used. Example items include "Worrying thoughts go through my

mind". The HADS-A subscale shows adequate internal consistency (Cronbach's α = 0.82; Crawford et al., 2001).

Statistical Analyses

All analyses were completed using RStudio (R Core Team, 2022) and JASP (Jasp Team, 2023).

In Part 1 of these analyses, CHYPS-V factors were assessed against participants' reported diagnoses. To investigate patterns of visual sensitivities across the four CHYPS-V factors, descriptive analyses included the calculation of mean z-scores for each subscale, standardized against participants who reported no clinical diagnoses (n = 933). Data met assumptions of normality (Kline, 2008) and homoscedascity (Osborne & Waters, 2003). The forced entry method was therefore used to conduct four multiple regressions to assess the predictive ability of self-reported diagnoses upon each of the CHYPS-V subscales. Age and gender were also included to control for their influence. Analyses focused only on diagnoses for which we had sufficient power: ADHD, autism, BED, depression, dyslexia, dyspraxia, fibromyalgia, GAD, migraine, OCD, panic disorder, PTSD, PPPD, social anxiety. Phi coefficients were also calculated to assess and display the association between co-occurring diagnoses.

In Part 2, I explored the association between the CHYPS-V factors and other relevant questionnaires using network analysis. The *qgraph* (Epskamp et al., 2012) package was used to estimate the network structure of our variables, using the subscale scores for each factor of the CHYPS-V (IVE, Brightness, Strobing, Pattern), as well as the total scores for MSQ, VVAS, and symptom scores for each of the seven HADS-A items. These scores represent the network's nodes, whilst its edges are the associations among these symptom scores. To control for false positives, the least absolute shrinkage and selection operator (lasso; Tibshirani, 1996) was used, which reduces small edges (likely due to noise) to zero (Chen & Chen, 2008; Van Borkulo et al., 2014). The graphical lasso procedure used Spearman correlations to estimate the network (to ensure a positive definite matrix), meaning that edges represent partial correlation coefficients which control for the other relationships within the network.

In the graphical representation of the network, node placement is decided using a modified (Epskamp et al., 2012) version of the Fruchterman-Reingold (Fruchterman & Reingold, 1991) algorithm which places connected or stronger nodes close to each other. However, small differences in the input to this algorithm can cause highly different node

placement, meaning that statistical indices (e.g., centrality) are more informative to interpret than graphical node position.

The centrality of all nodes was calculated; as has been the case in previous literature (Fried et al., 2016), node strength (the sum of all associations a node shows with all other nodes; Opsahl et al., 2010) will be the focus of these analyses. Using guidelines proposed by Epskamp et al. (2018), we also estimated the robustness of edge weight and centrality parameters using the *bootnet* package. Non-parametric bootstrapping (nboots = 1000) was used to estimate edge weight accuracy with 95% confidence intervals. A case-dropping bootstrapping procedure was used to investigate the stability of centrality indices and calculate a correlation stability coefficient (CS-coefficient). CS (c*or* = 0.7), as is recommended (Epskamp et al., 2018), represents the maximum proportion of cases which can be removed whilst maintaining with 95% probability that correlations between the original networks and case-dropped networks is 0.7 or higher. It is recommended that CS-coefficients should be at least greater than 0.25, and preferably greater than 0.50 (Epskamp et al., 2018).

The spinglass algorithm within the *igraph* package (Csardi, & Nepusz, 2006) was subsequently used to identify communities within the identified network; that is, where nodes in the network group or cluster together. This algorithm is a data driven approach to community identification which is well established in network science (Yang et al., 2016). Following community identification, the package *networktools* was used to investigate the presence of bridge nodes, defined as nodes that play a key role in connecting groups of nodes (communities) to each other. Aligning with previous work supporting the robustness of the indicator (Jones et al., 2021), bridge strength was used to evaluate bridge symptoms. This parameter represents the sum of edge weights connecting a node to all nodes in other communities. The 80th percentile cut off (Jones et al., 2021) identified bridging nodes.

Results

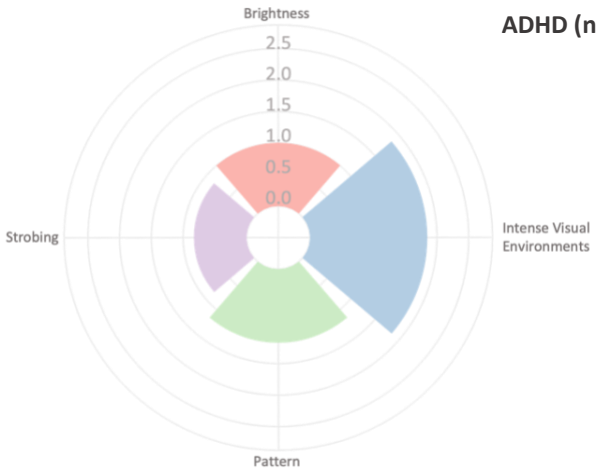
Part 1. Visual sensitivities across diagnoses

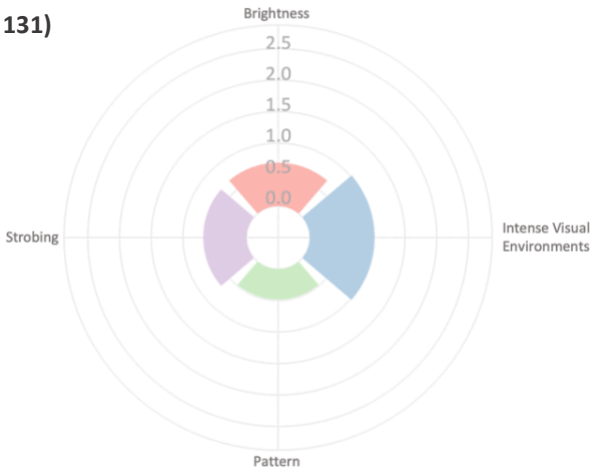
Mean z-scores standardized against individuals reporting no clinical diagnoses are displayed in Figure 1. Considering z-scores, conditions including BED, GAD, depression, and migraine showed reasonably consistent increases across CHYPS-V factors (i.e., no difference larger than 0.5 across factors). However, the remaining diagnoses displayed a comparatively less isotropic pattern, with the highest z-scores in the IVE factor.

It is possible that some cross condition differences are masked by the frequent comorbidities present in the sample (see Figure 2 for graphical representation of comorbid diagnoses). Figure 1 also therefore displays unstandardized regression coefficients for each clinical diagnosis and area of neurodiversity, taken from multiple regression models for each CHYPS-V factor that included all diagnoses. In these analyses, cross-factor patterns are more diverse. Significant increases in all CHYPS-V factors associate with reported diagnoses of autism, fibromyalgia, migraine, and PPPD. A reported diagnosis of PTSD significantly associated with IVE, Brightness, and Pattern whilst panic disorder associated with IVE and Strobing. Significant increases in Strobing and Pattern were associated with depression, whereas a diagnosis of social anxiety associated with Brightness scores only. Gender also showed significant associations with all CHYPS-V subscales; reporting female gender was significantly associated with increases across all four factors. In contrast, age showed significant associations with only IVE and Strobing subscales.

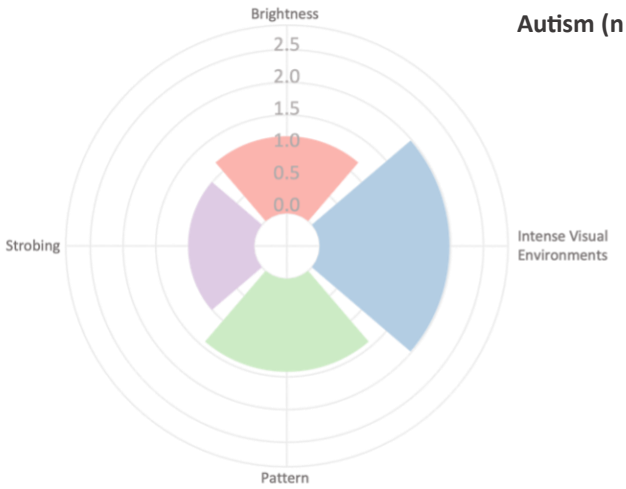
The significance of regression coefficients is displayed in Table 2. Each regression model was also significant overall [IVE: $F (16, 1824) = 30.89$, $R^2 = .22$, $p < .001$], [Brightness: $F (16, 1824) = 29.20$, $R^2 = .20$, $p < .001$], [Strobing: $F (16, 1824) = 25.39$, $R^2 = .18$, $p < .001$], [Pattern: $F (16, 1824) = 30.18$, $R^2 = .21$, $p < .001$].

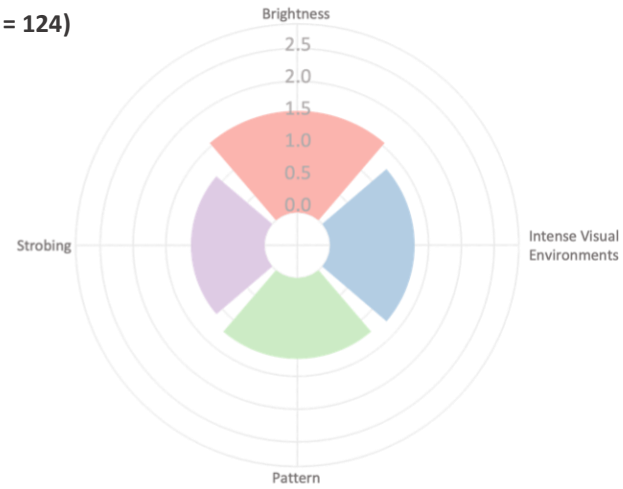
ADHD (n = 131)



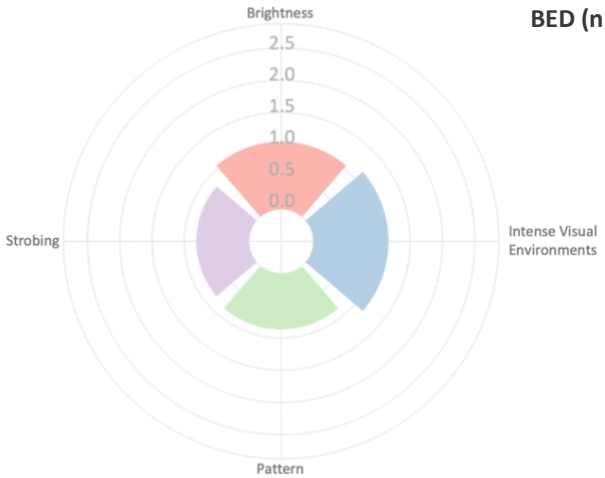


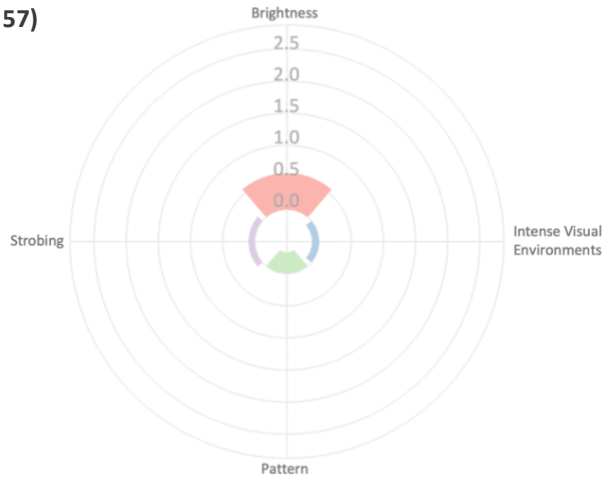
Autism (n = 124)



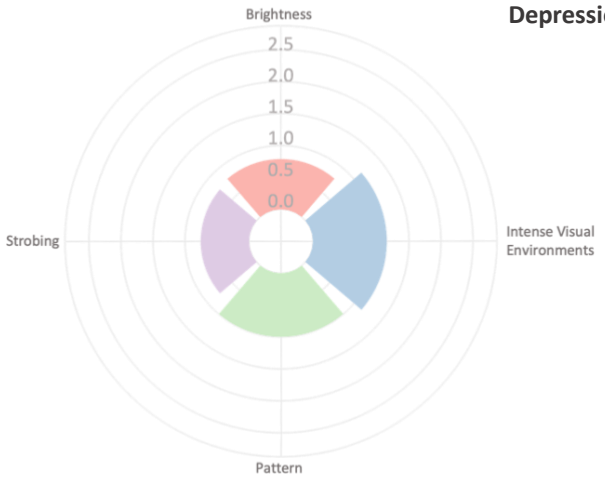


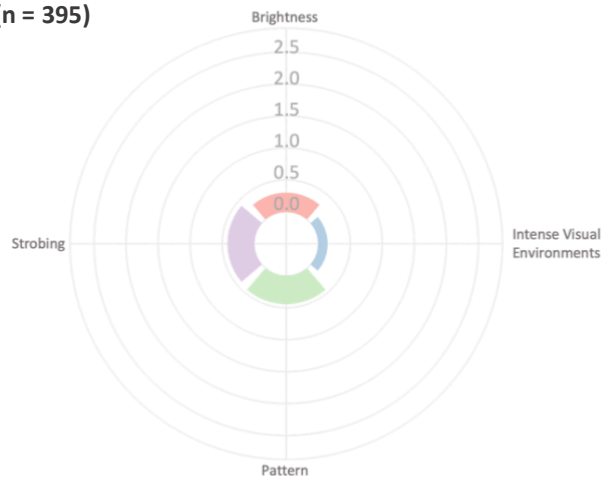
BED (n = 57)



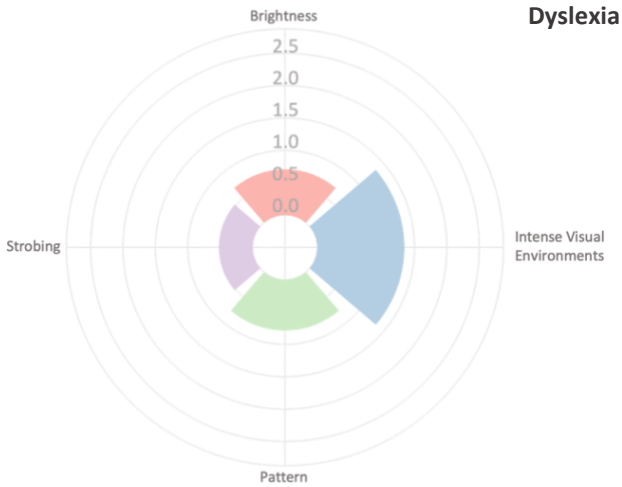


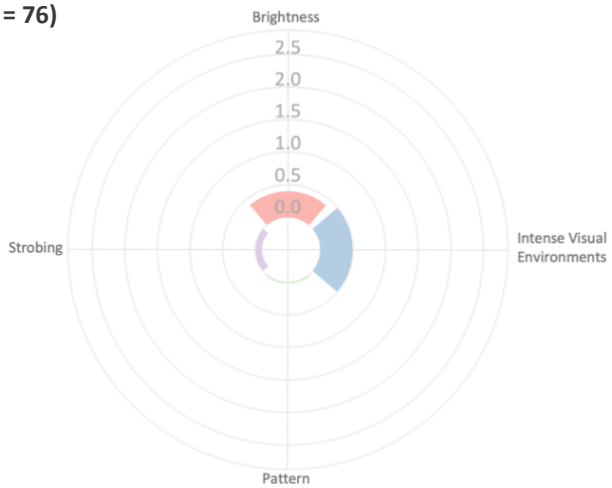
Depression (n = 395)



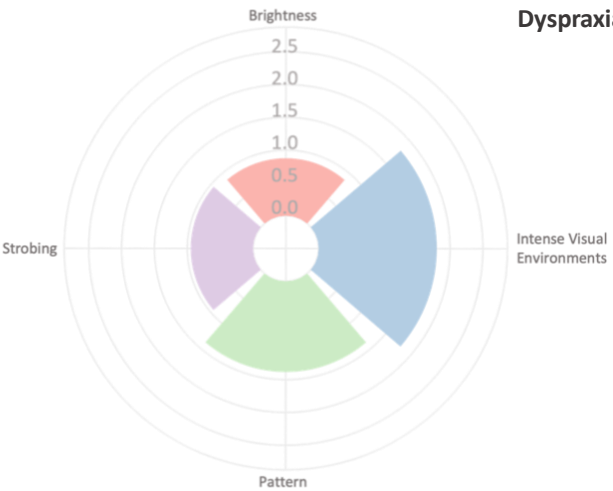


Dyslexia (n = 76)

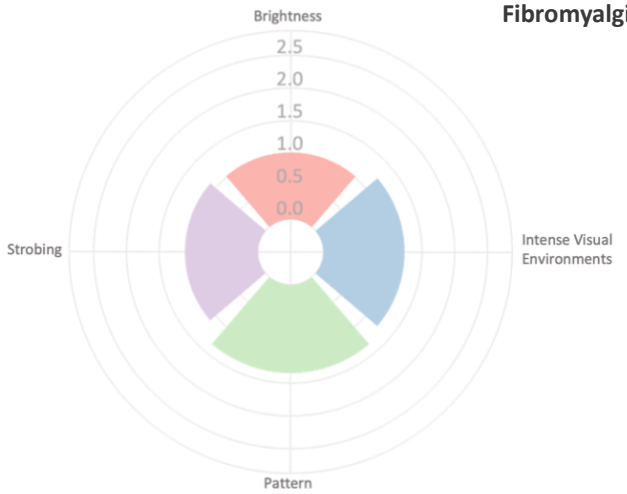


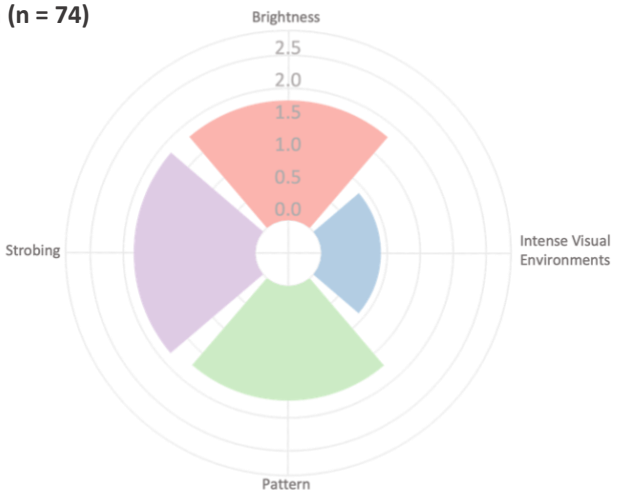


Dyspraxia (n = 34)

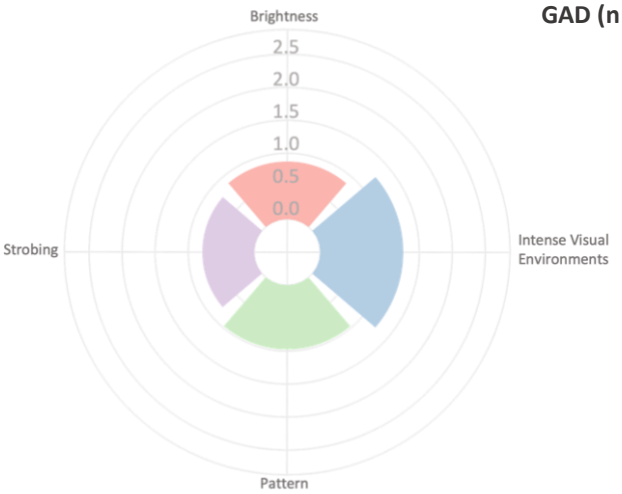


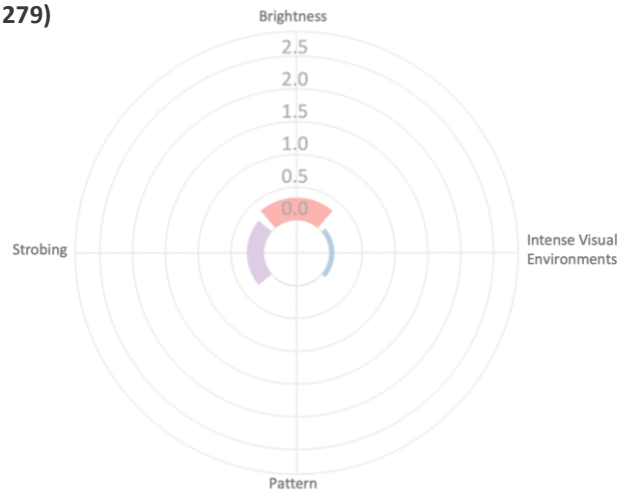
Fibromyalgia (n = 74)



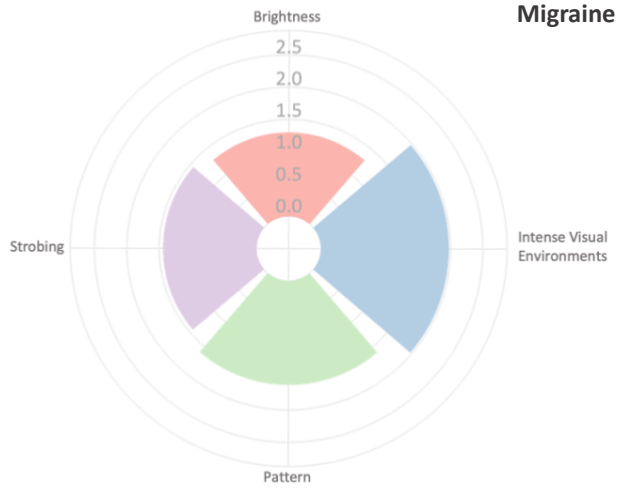


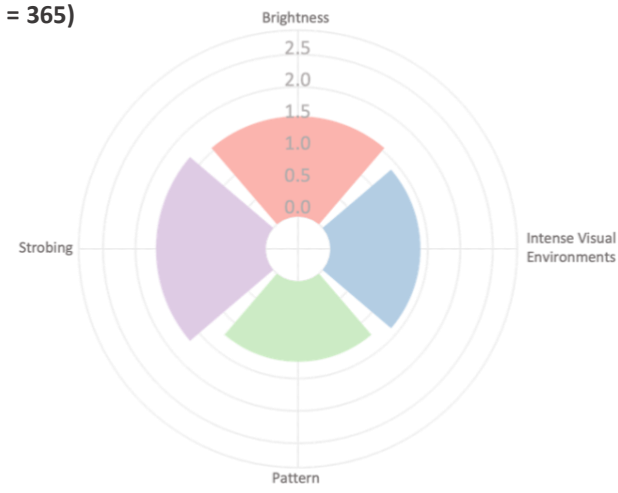
GAD (n = 279)



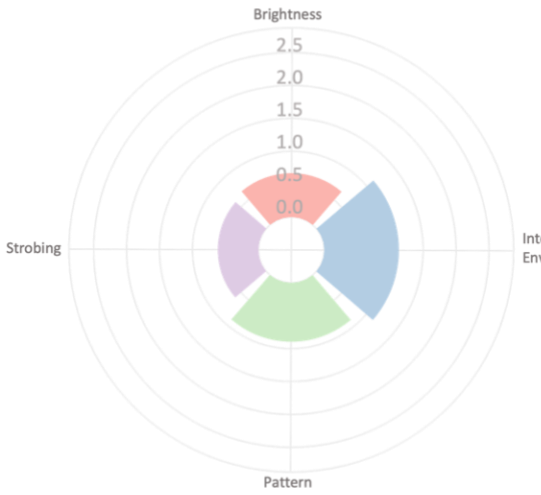


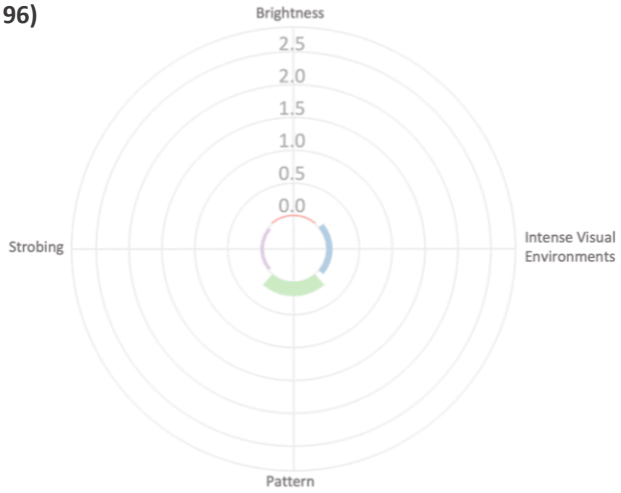
Migraine (n = 365)



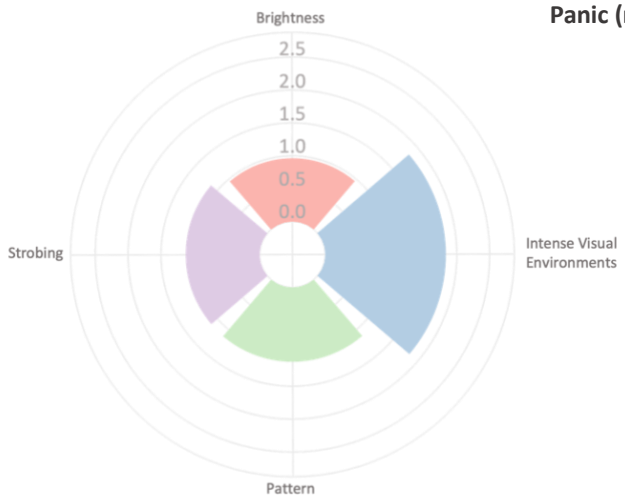


OCD (n = 96)

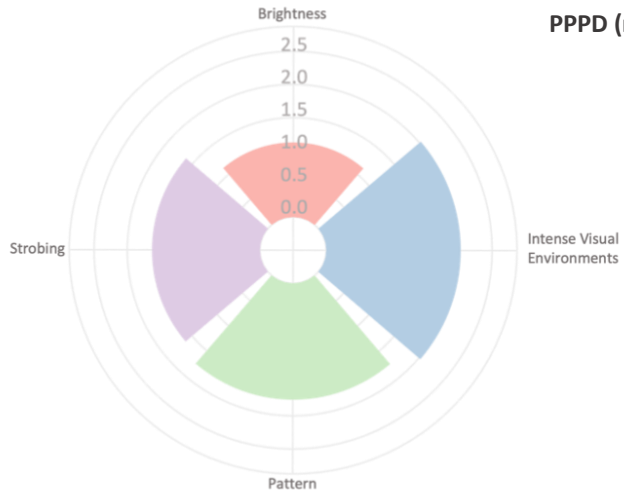


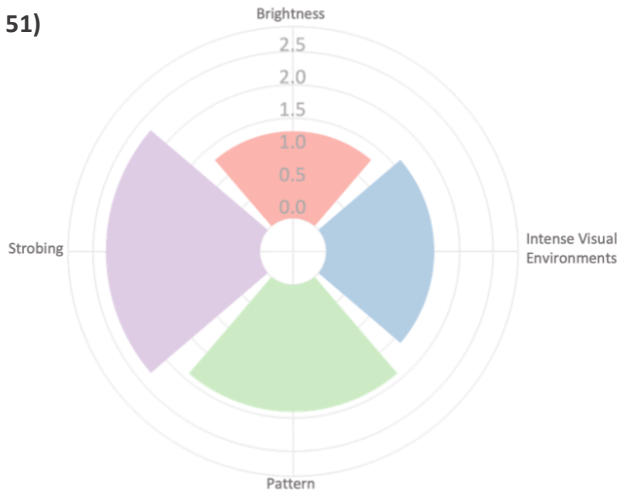


Panic (n = 72)



PPPD (n = 51)





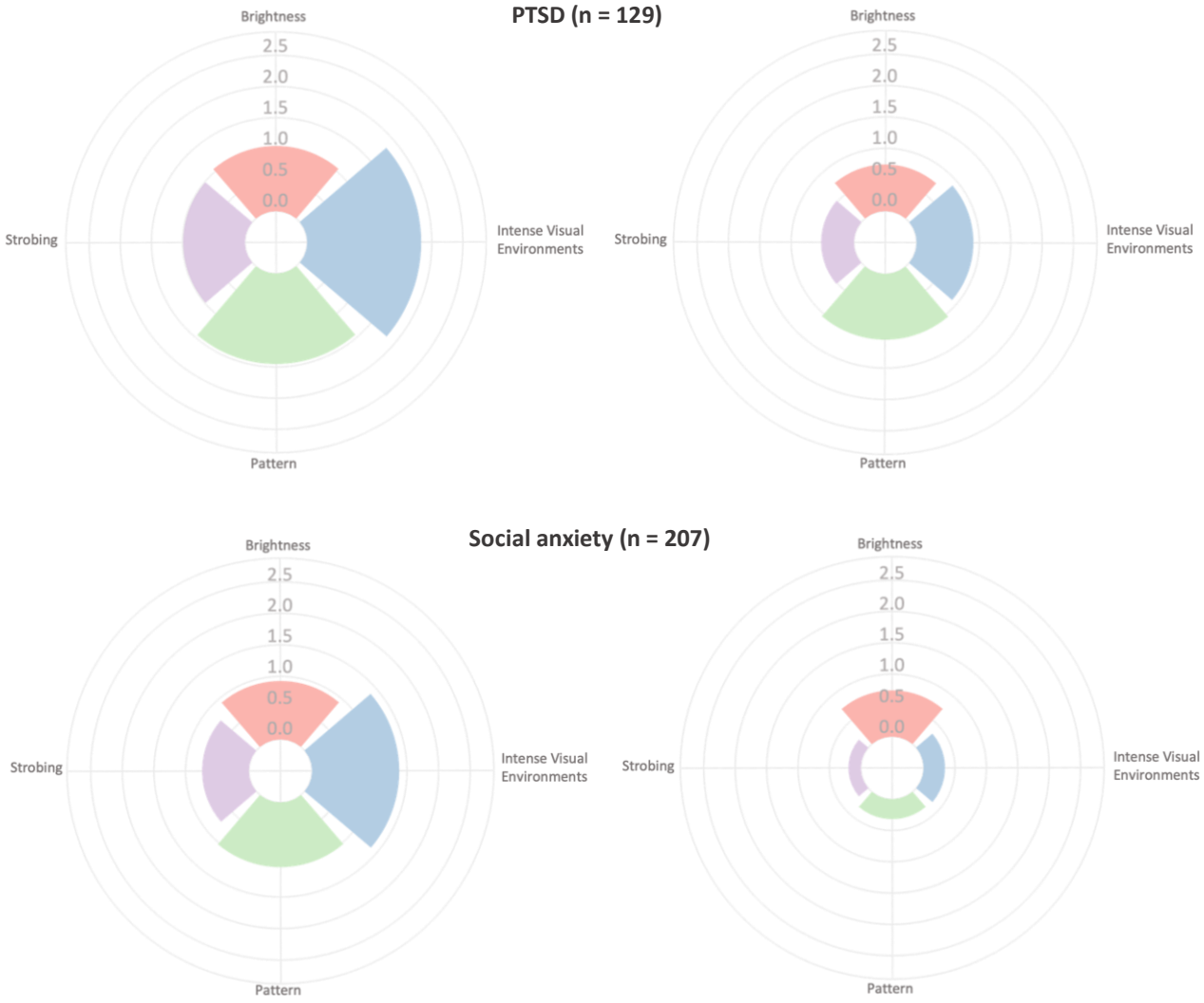


Figure 1. Per diagnosis, graphs displaying z-scores for each factor of visual sensitivity (*left*) standardized against participants reporting no clinical diagnoses (n = 933) and unstandardized regression coefficients (*right*) taken from regression analyses including all diagnoses, plus age and gender. *Note.* ADHD = attention deficit hyperactivity disorder, BED = binge eating disorder, GAD = generalized anxiety disorder, OCD = obsessive compulsive disorder, PPPD = persistent perceptual postural dizziness, PTSD = post-traumatic stress disorder.

	Brightness		IVE		Pattern		Strobing	
	B	SE	B	SE	B	SE	B	SE
ADHD	0.69*	0.35	1.02*	0.22	0.49	0.27	0.68*	0.32
Autism	1.55*	0.34	1.29*	0.22	1.23*	0.27	1.12*	0.32
BED	0.57	0.47	-0.11	0.30	-0.33	0.37	0.10	0.43
Depression	0.30	0.23	0.15	0.15	0.45*	0.18	0.42*	0.21
Dyslexia	0.40	0.41	0.49	0.26	0.02	0.32	-0.10	0.38
Dyspraxia	0.04	0.60	0.65	0.38	0.66	0.48	0.51	0.55
Fibromyalgia	1.55*	0.41	1.39*	0.26	1.24*	0.33	1.69*	0.38
GAD	0.34	0.27	0.08	0.17	0.02	0.21	0.26	0.25
Migraine	1.82*	0.20	0.90*	0.13	1.74*	0.16	1.84*	0.19
OCD	0.03	0.37	0.10	0.24	0.22	0.29	-0.05	0.34
Panic	-0.08	0.44	0.70	0.28	-0.17	0.35	0.69*	0.40
PPPD	1.31*	0.49	1.62*	0.31	1.91*	0.39	2.31*	0.45
PTSD	0.74*	0.34	0.91*	0.21	1.05*	0.27	0.52	0.31
Social anxiety	0.74*	0.29	0.34	0.19	0.32	0.23	0.20	0.27
Age	-0.01	0.01	-0.01*	-0.01	-0.01	0.00	0.02*	0.01
Gender	1.82*	0.16	0.57*	0.57	1.13*	0.13	1.25*	0.15

Table 2. Unstandardized coefficients (and associated standard errors) taken from four regression analyses in which all variables were entered to determine their association with each of the CHYPS-V factors. *Note.* IVE = Intense visual environments, ADHD = attention deficit hyperactivity disorder, BED = binge eating disorder, GAD = generalized anxiety disorder, OCD = obsessive compulsive disorder, PPPD = persistent perceptual postural dizziness, PTSD = post-traumatic stress disorder. * $p < .05$.

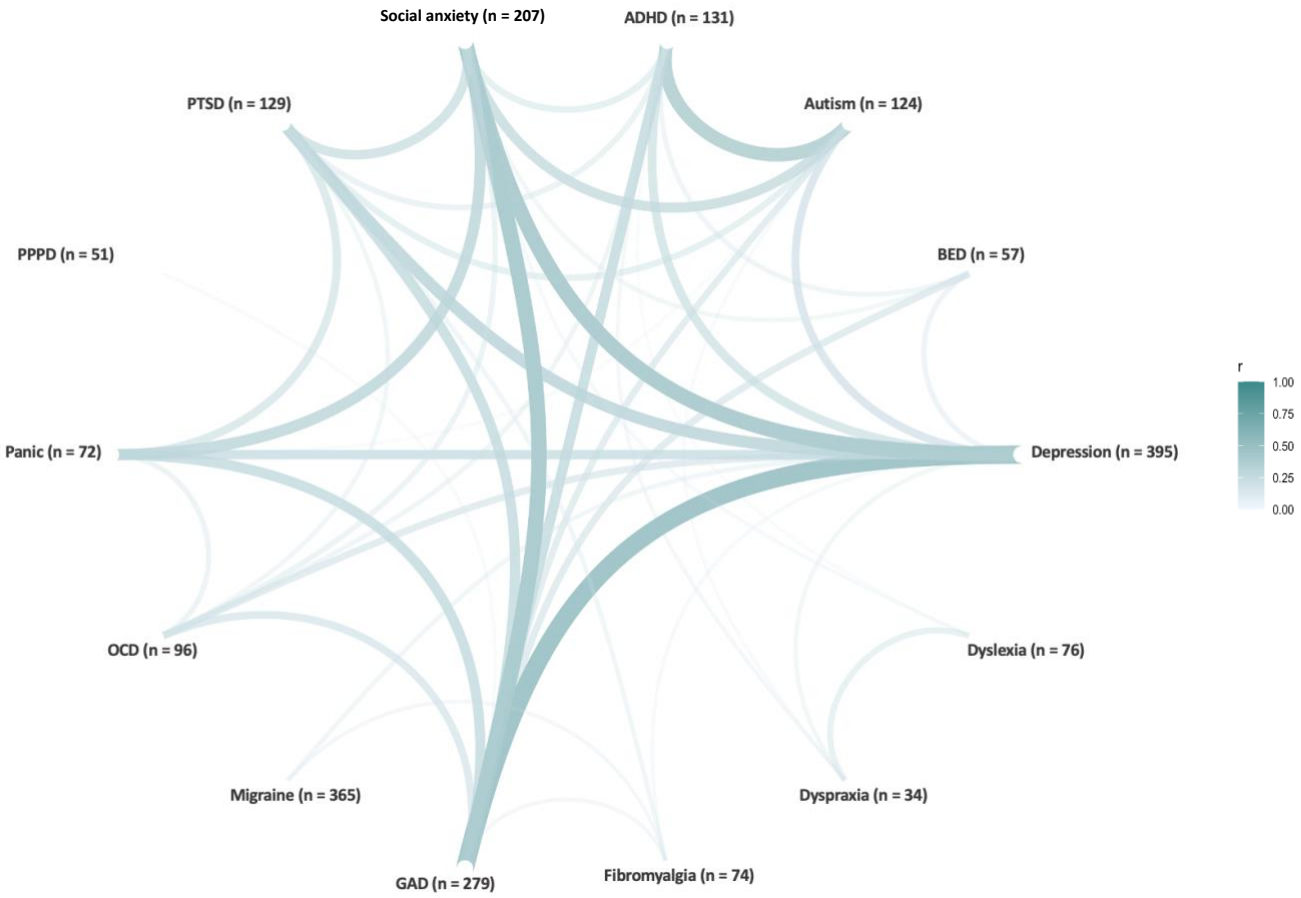


Figure 2. Graphical representation of comorbid diagnoses within the sample (n = 908), calculated based upon phi coefficient between each self-reported diagnosis or area of neurodiversity. Only coefficients > .10 are displayed. *Note ADHD = attention deficit hyperactivity disorder; BED = binge eating disorder; GAD = generalized anxiety disorder; OCD = obsessive compulsive disorder; PPPD = persistent postural perceptual dizziness; PTSD = post-traumatic stress disorder.*

Part 2. Network estimation for visual sensitivities, anxiety, migraine, and visual vertigo.

The estimated network is displayed in Figure 3. The network was positively connected, aside from a very small negative edge weight between the CHYPS-V Strobing factor and the HADS-A Worry item *("Worrying thoughts go through my mind")*. CHYPS-V subscales were among the most highly connected with each other, as were the HADS-A items. Considering centrality indices, Figure 4 displays node strength centrality. The most central node was the Panic item of the HADS-A (*"I get sudden feelings of panic"*), followed by the IVE subscale of the CHYPS-V, and the Worrying

thoughts HADS-A item. HADS-A items relating to experience butterflies and feelings of restlessness and were the least central.

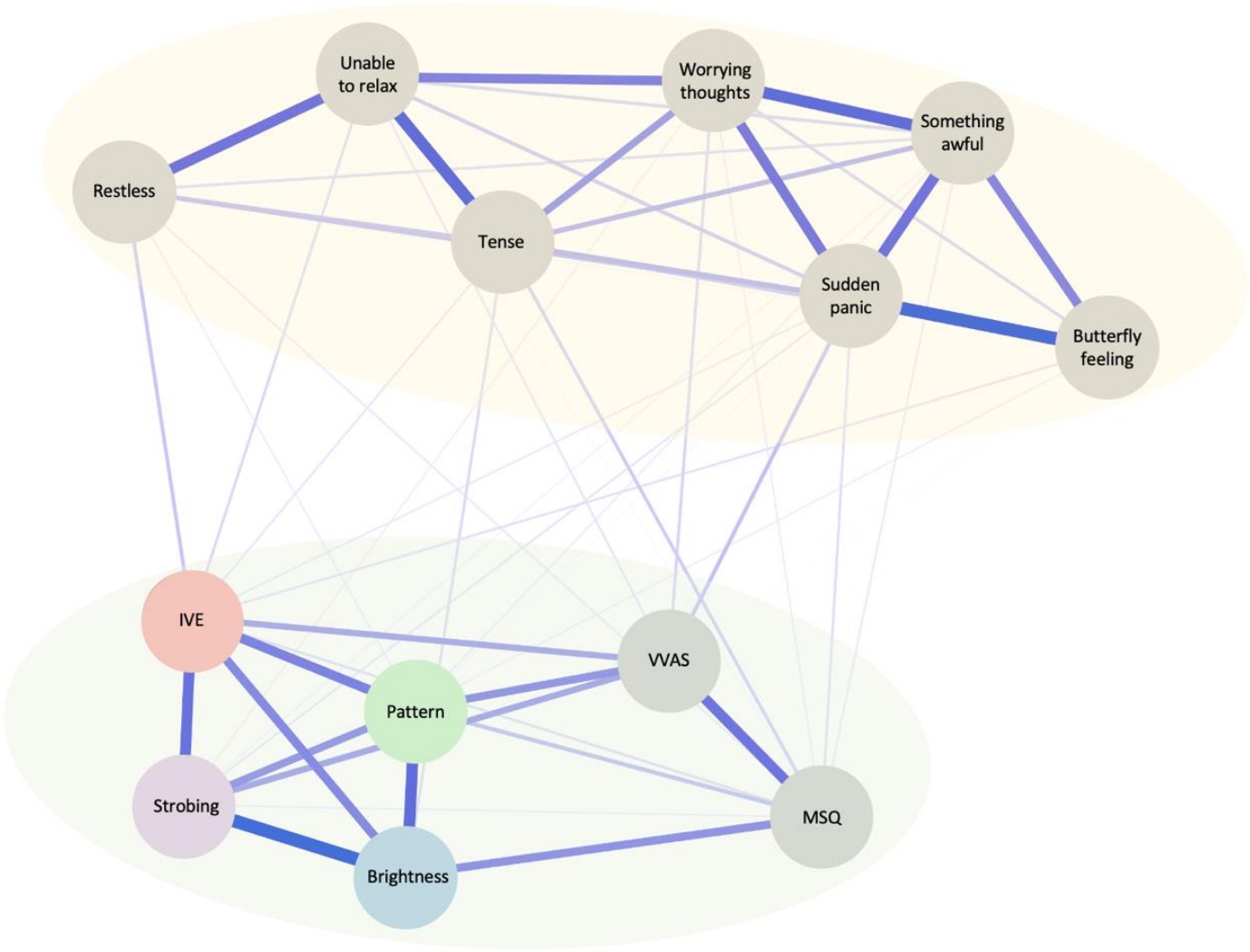


Figure 3. Network analysis containing HADS-A items, CHYPS-V subscale scores, and total VVAS and MSQ scores. Blue lines represent positive associations whilst red indicates negative. The thickness of the lines indicates association strength. Layout is decided by an adjusted Fruchterman-Reingold algorithm (see *Statistical Analyses*) where central nodes are placed towards the middle of the plot. Yellow shading indicates Community 1 (anxiety symptoms) and green indicates Community 2 (visual sensitivity) as defined by the spinglass algorithm. *Note:* IVE = Intense visual environments, VVAS = Visual Vertigo Analogue Scale, MSQ = Migraine Screening Questionnaire.

The spinglass algorithm defined two communities within the network; Community 1 included all HADS-A items (an anxiety symptoms cluster), and Community 2 included all four CHYPS-V subscales, MSQ, and VVAS scores (a visual sensitivity cluster; see shading in Figure 3).

Bridge strength analyses using 80th percentile cut off (Jones et al., 2021) identified the IVE CHYPS-V subscale, MSQ scores, and the Panic HADS-A item as bridging nodes. This suggests that these symptoms are key in associations between anxiety symptoms and experiences relevant to subjective visual sensitivities. Stability analyses (see Figure 5) showed both strength and bridge strength indices to be stable following case-dropping bootstrapping (correlation stability coefficients = 0.75, 0.52 respectively).

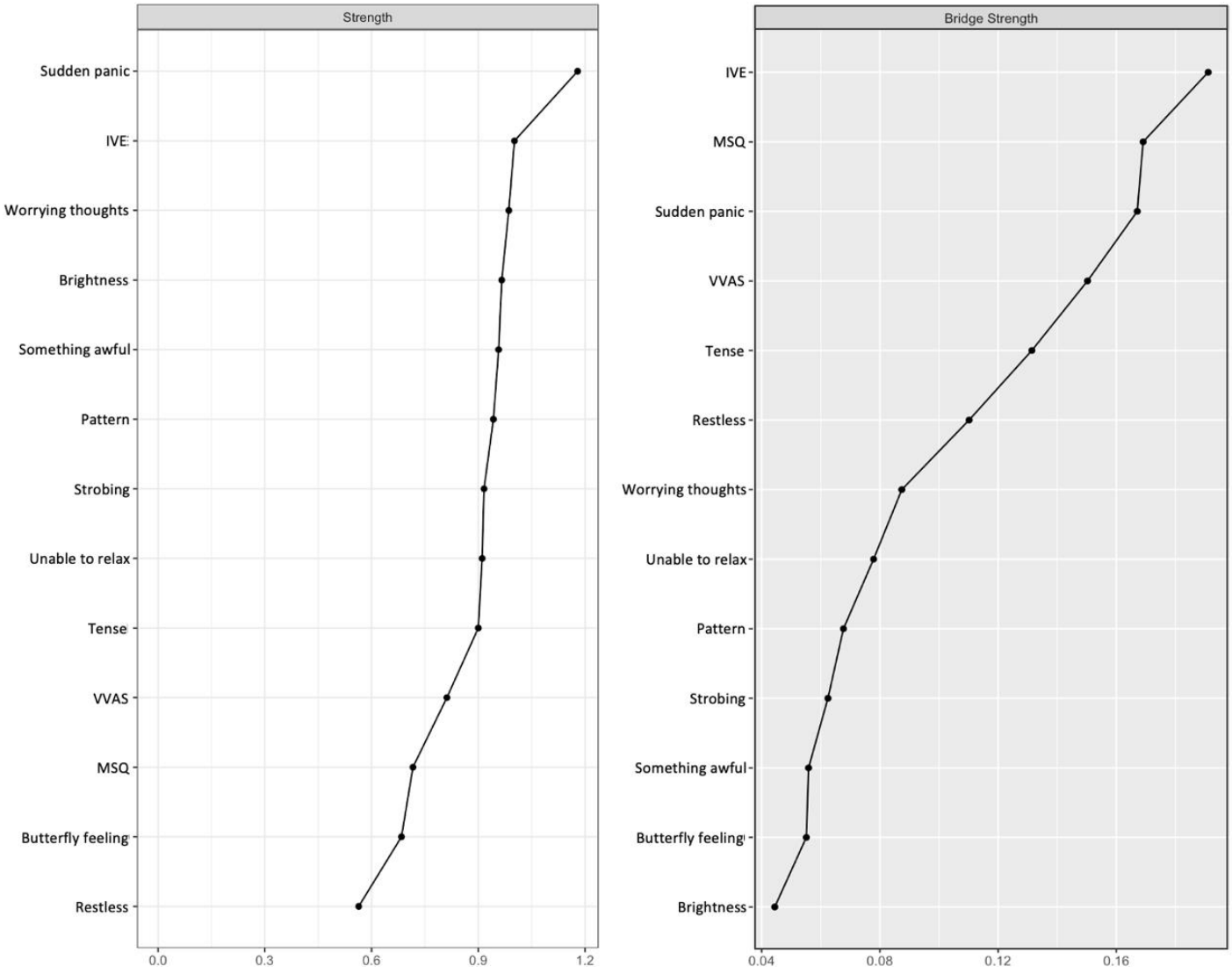


Figure 4. Strength and bridge strength centrality indices for the network. *Note: IVE = Intense visual environments, VVAS = Visual Vertigo Analogue Scale, MSQ = Migraine Screening Questionnaire.*

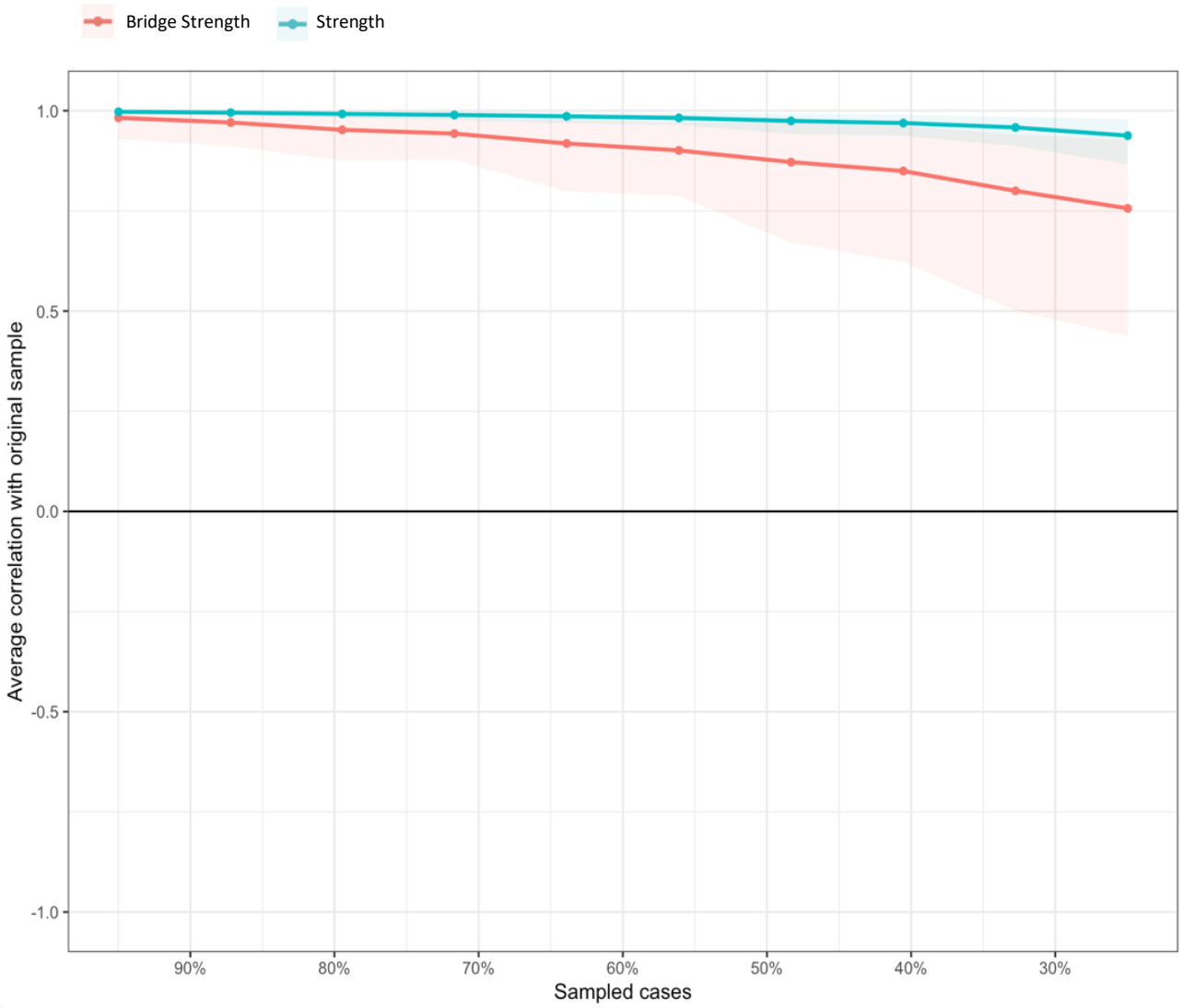


Figure 5. Results of case-dropping bootstrapping analyses displaying average correlations between centrality indices (Bridge strength and Strength) across subset samples.

Discussion

These analyses sought to investigate cross-diagnosis differences in factors of visual sensitivity before considering the relationship between these factors and anxiety symptoms more specifically.

Differences across factors of visual sensitivity

Across diagnoses, increases in mean scores when compared to participants reporting no clinical diagnoses was greatest in the IVE factor of the CHYPS-V. This suggests that experiences of visual sensitivity to cluttered spaces, supermarkets, or high visual motion environments might be particularly useful in distinguishing visual sensitivity experienced by individuals with clinical diagnoses from those without.

There are a number of possible explanations for the specific relevance of this factor. For instance, the IVE items describe circumstances of visual sensitivity that are characterized by multiple sources of visual input (crowds, supermarkets, clutter). In contrast, items from other subscales often describe a more individual source of discomfort, e.g., patterned clothing, flashing lights, direct sunlight. A reduced ability to adapt to incoming, numerate sensory stimuli may contribute to subjective feelings of sensitivity, as the perceptual system does not reduce ongoing activation in response (Ward, 2018). There is evidence to suggest reduced adaptation to numerosity in children with autism (Turi et al., 2015), in whom visual sensitivities are common (Robertson & Simmons, 2013). However, the extent to which reduced adaptation to numerate stimuli is present in other diagnoses and areas of neurodiversity, and its specific mechanistic effects upon sensitivity to IVE, requires further study.

A second, not mutually exclusive, possibility is that discomfort in responses to IVEs might be particularly increased in individuals susceptible to anxiety, as the multiple sources of visual input are perceived as overwhelming. Indeed, existing work reports individuals using terms like ‘overwhelmed’ to describe visually busy environments, whilst describing more of a pain-based reaction to striped visual images (Parmar et al., 2021). As many clinical diagnoses investigated here are known to associate with increased symptoms of anxiety (e.g., autism; Zaboski & Storch, 2018, ADHD; Schatz & Rostain, 2006, fibromyalgia; Alok et al., 2011, migraine; Lantéri-Minet et

al., 2005), visual sensitivities in this domain could be particularly increased due to these comorbid experiences.

Regression analyses were subsequently used to control for the potential influence of comorbid diagnoses, which were common and complex in the sample. Results suggested some condition specific patterns of association with factors of visual sensitivity. For instance, a diagnosis of panic disorder significantly associated with IVE and Strobing only. This is consistent with existing reports that individuals with panic disorder show increased sensitivity to complex stimuli like supermarkets and crowds (Asmundson, Larsen, & Stein, 1998) and screen-based motion (Jacob et al., 1989), and suggests this effect endures when a range of diagnoses are statistically controlled for.

In contrast, a diagnosis of PPPD associated significantly with all CHYPS-V factors. PPPD is a debilitating dizziness disorder, with known sensitivity to situations measured by IVE, Strobing, and Pattern (Powell et al., 2021; Staab et al., 2017) subscales. This appears to be one of the first studies to confirm that visual sensitivities also extend to Brightness in individuals reporting a diagnosis of PPPD, even when controlling for relevant comorbid diagnoses such as migraine and anxiety.

Other diagnoses which significantly associated with all four factors of visual sensitivity include autism, fibromyalgia, and migraine. This aligns with existing evidence of increased visual sensitivities in these conditions (Dorris et al., 2022; Friedman & De Ver Dye, 2009; Marcus & Soso, 1989; Parmar et al., 2021; Schulz & Stevenson, 2021; Ten Brink & Bultitude, 2022; Wilkins et al., 2021), and similarly extends this work to account for comorbid diagnoses. The mechanisms underlying significantly increased visual sensitivities across all subtypes in these diagnoses specifically is not yet clear, although possibilities will be described in the General Discussion.

Divergent findings in these analyses should also be highlighted, however. For instance, a reported diagnosis of dyslexia did not significantly associate with any form of visual sensitivity when controlling for other reported diagnoses. This contrasts existing work which finds visual stress (discomfort particularly triggered by flickering stimuli and repeating patterns) to be increased in children with dyslexia. However, much of this work (Kriss & Evans, 2005; Singleton & Henderson, 2007; Singleton & Trotter, 2005) has relied on improvements in reading speed following the use of coloured overlays as a measure of visual stress. Arguably, improvements in

reading speed do not necessitate the presence of visual sensitivity symptoms. More recent work has identified high visual stress in adults with dyslexia using both coloured overlay reading rate and the Visual Processing Problems Inventory (Singleton & Trotter, 2005), a questionnaire measure which largely focuses on perceptual distortions when reading. However, as discussed in Chapter 5, sensitivity to repeating patterns and flickering lights is not necessarily equivalent to discomfort whilst reading (evidenced as items relating to reading were not retained in the CHYPS-V). Indeed, Saksida et al. (2016) report children with dyslexia show similar levels of visual sensitivity to striped patterns (measured by the Pattern Glare task) as other children, suggesting that distortions whilst reading are likely dissociable from subjective visual sensitivities. This aligns with the analyses presented with this chapter, suggesting that when measuring visual sensitivity symptom endorsement (rather than intervention response or distortions whilst reading) and controlling for comorbid diagnoses, individuals with dyslexia do not report increased visual sensitivities.

Similarly, adults with developmental co-ordination disorder have previously been found to score significantly higher in the visual hypersensitivity subscale of the GSQ (Mayes, 2021), in analyses where participants with co-occurring neurological or neurodevelopment diagnoses were removed. Differences in methodology may influence these divergent findings; for instance, differences in diagnostic approach (confirmed diagnoses of DCD used by Mayes (2021) versus self-reported dyspraxia as is reported in this chapter), or in exclusion criteria (only comorbid neurodevelopmental diagnoses were excluded by Mayes, whereas a range of diagnoses were statistically controlled for in this chapter). It is possible that visual sensitivities are explained by comorbid diagnoses in dyspraxia, as reported here, however further work is therefore needed to confirm differences in visual sensitivities in this group.

The sensory differences of adults with binge eating disorder have not previously been investigated, and these analyses suggest that visual sensitivities are not increased when controlling for co-occurring conditions. It is possible that sensory differences might manifest in other sensory modalities however, or, as recent hypotheses suggest, hypo-sensitivities may be present (Nimbley et al., 2022).

Of particular interest is the lack of association between anxiety disorders (e.g., GAD) and visual sensitivities when controlling for co-occurring diagnoses, given reliable relationships are

found between subjective sensitivities and anxiety symptoms in existing literature (Engel-Yeger & Dunn, 2011b; Isaacs et al., 2020; Lewin et al., 2015) and were supported in Chapters 2, 3, and 5. For instance, in analyses described in Chapter 3, anxiety associated with sensory sensitivities in regression analyses which controlled for comorbid diagnoses. However, participants were asked if they had a diagnosis of "Anxiety", whilst in the current study they were afforded more specific options ("Generalized Anxiety Disorder", "Social Anxiety", "Panic Disorder"). It is possible therefore that the significant association between anxiety and sensitivity in Chapter 3 was driven by participants with other anxiety disorders, particularly those which show significant associations here.

Further, there is limited existing work investigating sensitivities in individuals with diagnoses of GAD specifically. One study found adults reporting a diagnosis of GAD scored significantly higher on the HSPS and sensory gating inventory (Troutwine, 2021), which both include some items relating to subjective sensitivities. Cervin (2023) also reported that children with OCD and other anxiety disorders (including GAD) have significantly higher scores on the AASP, even when controlling for comorbid diagnoses of ADHD or autism (Cervin, 2023). However, this work also investigated unique associations between internalizing symptom dimensions and sensory sensitivities. These analyses found only ordering (an OCD symptom), panic, and social anxiety symptoms to uniquely associate, with other symptoms (including generalized anxiety) remaining non-significant.

This aligns with the non-significant associations between OCD and GAD and visual sensitivities found here. For instance, it suggests that, when controlling for comorbid diagnoses, sensitivities may not associate as reliably with OCD at the diagnosis level (as was investigated here) but be contingent on specific symptoms which would be expected to vary across individuals given the heterogeneity of the condition (Bragdon & Coles, 2017). Similarly, the symptom analyses reported by Cervin (2023) also support the notion that specific aspects of anxiety associate with subjective sensitivities to a greater extent than generalized symptoms. Important diagnostic differences between GAD and other anxiety disorders may therefore underlie these divergent findings; for example, it has been noted that the diagnostic criteria for diagnoses such as panic disorder, social anxiety, and PTSD are more physiologically oriented than those for GAD (Troutwine, 2021), and differences in physiological and neural activity are found in empirical work

(e.g., Lang & McTeague, 2009; Clancy et al., 2017). These symptom differences could contribute to differential associations between anxiety disorders and visual sensitivities. However, it may also be the case that visual sensitivities are less affected in OCD and GAD when compared to sensitivities in other modalities. There is evidence to suggest tactile and oral sensitivities are particularly affected in OCD (Dar et al., 2012; Taylor et al., 2014), for example.

In considering the regression analyses described in Part 1 of this chapter, it is worth noting that many of the diagnoses are highly comorbid with each other (e.g., depression, anxiety disorders) and thus the consequences of statistically controlling for the influence of each may be somewhat unpredictable. For instance, given that anxiety disorders and depression so commonly co-occur (Hirschfeld, 2001) often with a range of other comorbidities (e.g., Martín et al., 2019; Smitherman et al., 2013), removing the influence of other diagnoses may represent a minority circumstance, and thus be less representative of individual experience. Although results described here are intuitive in terms of existing literature and understanding of sensitivities, further discussion of the implications of this statistical approach is provided in the General Discussion.

Finally, demographic variables were found to significant associate with factors of visual sensitivity. Across all four subscales, gender associated with visual sensitivities independently of age and reported clinical diagnoses. Specifically, female participants had higher sensitivity, consistent with the analyses reported in Chapter 2 and in existing literature (e.g., Engel-Yeger, 2012, Ueno et al., 2019, Ranford et al., 2020). Age was also associated with Strobing and IVE factors, although coefficients were small. Previous work has found changes in pattern induced distortions with age (Evans & Stevenson, 2008; Qi et al., 2019), and reduced interictal visual sensitivities in adults with migraine past age 50 (Kelman, 2006). As the current sample had a mean age of approximately 55, our findings are consistent. The mechanisms which contribute to age related change in visual sensitivity may be neural (e.g., differences in myelin; Nielsen & Peters, 2000, or in neurotransmitters; Pitchaimuthu et al., 2017), but require specific investigation.

In summary, these analyses support consistent cross chapter themes that sensory sensitivities represent a transdiagnostic symptom. When compared to individuals reporting no clinical diagnoses, participants with a range of conditions and areas of neurodiversity display heightened visual sensitivities. However, this work also highlights the importance of considering

comorbid diagnoses in investigations of this kind, to prevent masking of condition-specific effects. This tendency for certain diagnoses to show differential associations with factors of visual sensitivities also requires explanation, for which the CHYPS-V could be of use in future research. Similarly, given differential associations between clinical diagnoses and factors of visual sensitivity, there is a need to investigate factors across other sensory modalities to ensure conclusions regarding sensitivities are specific.

Network analyses

In Part 2 of this chapter, network analyses sought to understand how factors of, and relevant to, subjective visual sensitivities relate to symptoms of anxiety as reported in an anxiety questionnaire (as opposed to a self-report diagnosis of anxiety). It is known that anxiety at both symptom and diagnosis level co-occurs with experiences of subjective sensory sensitivity (Engel-Yeger & Dunn, 2011b; Isaacs et al., 2020). However, there is limited evidence investigating the role of specific symptoms in these associations. The present network analysis also accounted for (summed) symptoms of migraine and visually-induced dizziness, which themselves are highly associated with both anxiety (Lantéri-Minet et al., 2005; Powell et al., 2020b) and visual sensitivity (Powell et al., 2021; Powell et al., 2020b; Wilkins et al., 2021).

Bootstrapping procedures showed the strength centrality indices (sum of edge weights from a given node) were stable and thus interpretable. The HADS-A items relating to Sudden panic *("I get sudden feelings of panic"*) and Worrying thoughts *("Worrying thoughts go through my mind"),* as well as the IVE factor of the CHYPS-V were most central to the network. Taking a causal systems perspective (Borsboom, 2008), this suggests that these nodes are more important in the development and maintenance of this network.

Two communities were identified within the network: one containing all anxiety symptoms, and the other containing CHYPS-V subscales, as well as MSQ, and VVAS scores. These are both theoretically intuitive, and supported by edge weights which were strongest between symptoms of the HADS-A subscale, and between CHYPS-V factors. Bridge strength indices were also calculated based upon each node's association with symptoms outside of its community. The Sudden panic symptom, MSQ, and IVE had the highest bridge centrality. Differential strength across indices should be noted here; for instance, worrying thoughts displayed less bridge

strength centrality when compared to node strength centrality, potentially because this item displays stronger within-community than between community associations.

Considering each bridging symptom more specifically, the bridging role of the CHYPS-V IVE factor between these communities is not necessarily surprising given the factor's content; items include visual sensitivities in supermarkets, cluttered spaces, when viewing crowds or environments with a lot of motion, and when there is 'lots of bright colours'. It is possible that these experiences show stronger associations with symptoms of anxiety because they induce a feeling of overwhelm, as the amount of visual information is subjectively too great. As previously described, items included in other CHYPS-V factors tend to assess sensitivities to visual input that is comparably singular (e.g., bright ceiling lighting, patterned clothing, flashing lights), and thus may not be experienced as overwhelming, although still uncomfortable. IVE may therefore act as a bridging factor because the tendency to feel overwhelmed by busy visual environments more readily co-occurs with the experience of anxiety when compared to others CHYPS-V factors.

Other bridging nodes include symptoms of migraine (defined by MSQ scores). Specifically, MSQ scores were among the lowest scoring in terms of node strength centrality but show high bridge centrality. This implies that symptoms of migraine do not necessarily maintain the wider network but appear important in the co-occurrence of visual sensitivities and anxiety symptoms. The bridging role of migraine symptoms likely hinges on the co-occurrence of the diagnosis with symptoms of anxiety (Lantéri-Minet et al., 2005) and experiences of visual sensitivity (Friedman & De Ver Dye, 2009). Importantly, the network analyses shows that factors of visual sensitivity still associate with specific symptoms of anxiety even with the inclusion of migraine symptoms, highlighting how these experiences are not conditionally independent. This aligns with evidence from Chapter 2, which described only a partial mediating effect of anxiety upon the relationship between migraine occurrence and subjective sensory sensitivities. The present analyses extend the specificity of this finding; migraine appears to be a key bridge symptom between the experience of anxiety and of visual sensitivities, and associations continue to exist independently.

The Sudden panic items of the HADS-A ("*I get sudden feelings of panic"*) was also identified as one of the nodes with the highest bridge strength. Higher bridge strength scores suggest that these symptoms are more important to the aetiology and maintenance of the community connections in the network (Beard et al., 2016), implying a role for subjective and

physiological feelings of panic. More broadly, other items relating to physiological symptoms of anxiety *("I feel tense or wound up", "I feel restless as if I have to be on the move")* also had higher bridge than psychological symptoms, such as "*Worrying thoughts go through my mind*". This suggests that feelings of panic rather than thought-based symptoms of anxiety may be more important in understanding associations with visual sensitivities. This provides interesting parallels with the regression analyses, where, when controlling for co-morbidities, it was the anxiety disorders argued to have a greater physiological component (e.g., panic disorder, PTSD) whose association with visual sensitivities survived.

Limitations

Conceptual limits of the network should be kept in mind when interpreting these findings. The current network model is weighted but undirected. That is, edges represent only association, and not directional causality. Using cross-sectional data, directed (causal) networks are difficult to estimate without specific and harsh assumptions (e.g., an absence of feedback loops; Epskamp et al., 2018) which are difficult to justify, particularly in psychological constructs. The directionality of the effect of bridge symptoms identified in this analysis therefore cannot be determined, particularly as bidirectional relationships between anxiety and visual sensitivities are theoretically possible. For instance, experiencing pain, discomfort, or overwhelm in response to visual stimuli could cause anxiety. Similarly, anxious individuals have been found to show a nonspecific enhancement of early visual processing (e.g., as exhibited by increased event related potentials; Michalowski et al., 2014; Wieser & Keil, 2020), which could lead to an over-responsivity to incoming sensory signals. Exploration of these findings using longitudinal or causal design which investigate how intervention on central or bridge nodes affects wider network activation is therefore required (e.g., see Robinaugh, Millner, & McNally, 2016). For example, it is of interest how the network might differ in individuals receiving intervention which targets the hyperreactivity of the autonomic nervous system (e.g., heart rate, trembling) without necessarily affecting subjective feelings (e.g., treatment using propranolol; Steenen et al., 2016). Reduced bridge strength in these groups would support the role of these symptoms in contributing to visual sensitivities.

It is also likely that some associations within the network are not causal. Whilst the network has largely been interpreted using a causal systems perspective (Borsboom, 2008), other theoretical models are relevant and not mutually exclusive. For example, common cause approaches (whereby an entity or diagnosis causes a set of symptoms) can apply, where some symptoms in this network may co-occur due to a common cause. This may be particularly relevant to the experience of migraine; specifically, both migraine and visual sensitivities may be driven by a common factor (e.g., heightened visual cortical excitability; Hibbard & O'Hare, 2015; Huang et al., 2003), rather than one explicitly causing another.

Limitations of a symptom based rather than sum score approach to represent anxiety should also be considered. While this better aligns with a causal systems perspective and acknowledges that not all symptoms are interchangeable indicators of an experience or diagnosis (Fried & Nesse, 2015a), it means that single items were used to measure symptoms. Future work investigating the role of specific anxiety symptoms in associations with visual sensitivities would benefit from using additional items (or measures) (Fried & Nesse, 2015b) to investigate constructs of interest, with a view to enhancing the reliability of these findings. For instance, replicating this work in combination with the State-Trait Inventory for Cognitive and Somatic Anxiety (STICSA; Grös et al., 2007) which includes more extensive items to differentiate forms of anxiety (i.e., cognitive vs somatic).

Overall summary

Overall, Part 1 showed that IVE is the most strongly reported visual sensitivity factor across many self-reported diagnoses related to mental health, neurodiversity, and functional neurology. However, when controlling for comorbidities in a regression, other more specific patterns emerged for how different diagnoses may be associated with different aspects of visual sensitivity. This provides a wealth of possibilities for further research and highlights the importance of considering comorbidities.

In Part 2, the network analysis presented had several clear conclusions. The IVE factor of visual sensitivity has a more central role in a network including anxiety symptoms than the other sensitivity factors, suggesting that these experiences may more commonly occur in anxious individuals. Feelings of panic showed both high node strength and bridge strength; this highlights

how somatic symptoms of anxiety, as opposed to excessive worry, may be important in understanding the relationship between subjective visual sensitivities and anxiety symptoms. Finally, although migraine was not necessarily central to the network as a whole, it showed high bridge strength, establishing that it is an important influence in the co-occurrence of anxiety and visual sensitivities. Causal design and consideration of how intervening in central nodes would reduce anxiety symptoms and aversive visual experiences is necessary to better understand the complex, interacting systems that contribute to the network.

Chapter 8: General Discussion

Overview of findings

This work has established a number of novel conclusions concerning the nature and experience of subjective sensitivities.

First, Chapter 2 used a large general population sample to establish that beyond known sensitivities to light and sounds during an attack, cross modal sensitivities are also present interictally in people with migraine. This work also investigated the role of anxiety, finding that anxiety symptoms only partially mediate the relationship between migraine and sensory sensitivities, suggesting that these symptoms are relevant to, although not sufficient, in explaining increased sensitivities in migraine.

Chapter 3 considered subjective sensitivities across self-reported clinical diagnoses and areas of neurodiversity finding that sensitivities are heightened across a diverse range of diagnoses, with evidence of condition-specific differences when using quantitative measures. Some associations with subjective sensitivities appeared to be accounted for by comorbid diagnoses, suggesting a need for future research and clinical practice to consider co-occurring conditions when identifying and managing differences in sensory experience.

Chapter 4 investigated the experience of subjective sensitivities using thematic analysis. Participants described sensitivities as impacting their quality of life in a variety of ways, across occupational capabilities, personal wellbeing, and social dynamics. The ways in which sensitivities are also coped with by participants was described, providing a foundation through which future research could investigate their relative efficacies. Exacerbating factors were also investigated, which may be beneficial in enhancing understanding of mechanism (to be discussed later) and additionally in psychoeducation efforts. Finally, content analyses described in this chapter demonstrated consistencies in sensory modalities which participants chose to describe as positive or negative.

Chapters 5 and 6 centred on discovering the factors of visual sensitivities and the development of a novel self-report measure, the CHYPS-V. The measure's sound psychometric properties were evidenced, as well as it's multidimensional nature. Across these chapters, and over 2700 participants, the CHYPS-V showed a highly consistent four bi-factor solution, suggesting that although visual sensitivities can be represented by a general factor, four additional specific

factors best characterize the experience across individuals (namely: Brightness, Pattern, Strobing, and Intense Visual Environments). This has clear implications for existing measures which are limited in their conceptual coverage and use only a limited number of items to assess what appears to be a multi-dimensional construct. Further, there are theoretical implications for our understanding of visual sensitivities and their causes, which will be subsequently described.

Finally, Chapter 7 extended the cross-condition analyses described in Chapter 3 to focus specifically on how factors of visual sensitivity (as defined by the CHYPS-V) differ across clinical conditions. Condition specific effects were described, and analyses which controlled for the co-occurrence of diagnoses further support the need to consider comorbid conditions in work of this kind. Subsequent network analyses investigated the relationship between visual sensitivities and symptoms of anxiety with more specificity; results suggested that somatic symptoms may be particularly important in understanding the association between these constructs.

Theoretical implications

The results from this thesis advance our understanding of sensory sensitivities in two main ways; 1) demonstrating that visual sensitivity can be sub-typed into four different categories, with a strong general factor, 2) illustrating that sensory sensitivities are transdiagnostic and share some similarities in their presentation across conditions. The theoretical implications of these two findings will now be discussed in the context of previous literature.

Sub-types of visual sensitivities

Chapters 5 and 6 described bifactor analyses which found that alongside a general factor, there are four specific factors of visual sensitivity which also capture individual variation in experience; these factors describe discomfort in response to Brightness, Strobing, Pattern, and Intense Visual Environments (IVE).

This represents a change to existing study, where definition and understanding of visual sensitivity has taken a more limited view. For instance, visual stress is described as discomfort in response to striped pattern or to flicker (conceptually similar to our CHYPS-V Pattern factor; Wilkins, 2021). Likewise, photophobia (potentially akin to the Brightness factor in our model) has

been described specifically as an aversion to light (Burstein, Noseda, & Fulton, 2019). Study of visual sensitivity mechanisms (e.g., Burstein, Noseda, & Fulton, 2019; Wilkins, 2021) have often been limited to these features, whilst work in this thesis establishes that visual sensitivity is a much broader construct, which can be sub-categorised into four subtypes of the experience, but also conceptualised as a global, general factor upon which these subtypes load.

The existence of four factors of visual sensitivity is theoretically consistent with findings in individuals with epilepsy. Specifically, seizure triggers are individualized, and can vary from flashing lights and patterns to fast moving graphics or television shows (Fisher et al., 2005). To illustrate, in a sample of participants with pattern sensitive epilepsy, approximately 41% also cited television as a precipitant, 7% also reported video-games, and 38% reported flashing lights (Radhakrishnan et al., 2005). Clearly therefore, sensitivity to one form of visual stimuli does not necessitate sensitivity to another, and trigger patterns can differ across individuals. It has been argued that intrinsic excitability in areas of visual cortex which code for specific visual attributes (e.g., pattern, colour) can give rise to these differences in precipitants (Radhakrishnan et al., 2005).

Similar mechanisms could readily apply to the four factors of visual sensitivity, explaining why an individual might report sensitivity to one visual stimulus but not another. For example, both retinal and cortical mechanisms are described as relating to sensitivity to light. Whilst ipRGCs and trigeminal nerve mediated release of neurotransmitters may be particularly important to some forms of photophobia (Noseda et al., 2019), imaging work finds participants who are more prone to discomfort from light stimuli show hyperexcitability in specific regions of the visual cortex (e.g., cuneus, lingual gyrus, posterior cingulate cortex, superior parietal lobules) in response (Bargary et al., 2015; Boulloche et al., 2010).

Similarly, discomfort in response to flickering light (conceptually covered by the CHYPS-V Strobing factor) correlates with evoked responses in early visual cortex (Gentile & Aguirre, 2020). With regards to the Pattern subscale, hyperexcitability in early visual areas is also thought causal; for example, whilst V1 shows maximal cortical activation in response to 3cpd stimuli, V2 typically shows low-pass spatial frequency tuning, with maximal response to approximately 0.3cpd (Huang et al., 2011; Singh et al., 2000). Interestingly, fMRI study in migraine finds that when participants are shown aversive patterns, V2's characteristic low pass tuning is absent, and the area instead

shows maximal activation in response to 3cpd (Huang et al., 2011) . Given V2's primary excitatory input is from V1, this supports the idea of excess excitation (or a lack of inhibition) in this region for participants with migraine. The use of precision ophthalmic tints subsequently reduced visual sensitivity to pattern and normalized V2 response, suggesting this activation is causative in experiencing repeating patterns as uncomfortable. This mechanism could extend to pattern sensitivities more generally.

Compared to the other CHYPS-V factors, IVE may be comparatively more complex in mechanism. Although instructions asked participants to focus on visual sensitivity, several of the environments described within this factor are inherently multimodal and social (e.g., supermarkets, crowds moving). Similarly, cognitive load is likely increased in these situations, via decision making in a supermarket or navigating through a large crowd. Aversive feelings to visual input in these scenarios may therefore be exacerbated by the concurrent demands of multimodal and social inputs, and executive function demands, perhaps implicating excitation in other areas of the cortex in the experience (e.g., primary motor cortex; Bolden et al., 2017).

In considering mechanisms relevant to each factor of visual sensitivity, it is important to acknowledge not only that a strong general factor was also identified, but additionally that visual sensitivity is unlikely to exist in isolation. That is, subjective sensitivities tend to be increased cross modally (e.g., see Chapters 2 and 3). This means that differences in individuals who experience a particular form of visual sensitivity must correlate across neural populations, other sensory regions, or cortical (or cognitive) mechanisms.

One such mechanism might be the way in which discomfort is interpreted. For example, existing theories are not exact in explaining why overactivation in the brain would be experienced as uncomfortable. Whilst some argue discomfort is a homeostatic mechanism to prevent metabolic stress or retinal damage (Hibbard & O'Hare, 2015; Wilkins et al., 2021), others note that uncomfortable stimuli do not always produce neural or retinal effects that the system could not cope with (Gentile & Aguirre, 2020). Instead, the subjective feeling of aversion may simply be what it feels like for the brain to be processing signals inefficiently (Gentile & Aguirre, 2020), or be a result of limbic system pathways which introduce emotional processing of discomfort, driving a desire to avoid the stimuli (Russo & Recober, 2013). Indeed, in animal models of photophobia, aversive reactions are accompanied by neural activation in the amygdala (Delwig

et al., 2012), and human study finds that amygdala activation correlates with the perceived unpleasantness of a stimulus, suggesting a role for limbic regions in feelings of aversion (Zald, 2003). It is possible that individual differences in any of these possible mechanisms through which feelings of discomfort are established contributes to a general capacity for experiencing subjective sensitivities. Specific within or across modality subtypes of sensitivity may depend more localised activity or connectivity (e.g., Ward, 2018). These mechanisms require further study however, which the CHYPS-V will be useful in informing.

In sum, the extent to which a person's visual cortex is prone to excitability (Bargary et al., 2015), the specific areas in which this occurs (Radhakrishnan et al., 2005), and the other cortical areas which are also implicated (e.g., amygdala, Russo, & Recober, 2013; primary motor cortex, Bolden et al., 2017), may explain individual differences in the four factors of visual sensitivities. The role of pathways and excitability outside of the visual cortex may be more relevant to some aspects of visual sensitivity than others (e.g., the role of cognitive load in IVE), however there must exist a consistent mechanism which means that visual sensitivities are more likely to coincide (as defined by the general factor), and additionally to co-occur with cross modal sensitivity.

Sensory sensitivities: a transdiagnostic experience

Throughout this work, it has been demonstrated that that sensory sensitivities occur across a range of clinical diagnoses and areas of neurodiversity, extending beyond those which have been the focus of much existing study (e.g., autism, anxiety, ADHD). This adds further support to recent proposals which suggests that a unique sensory domain should be incorporated into the dimensional Research Domain Criteria (RDoC) initiative, a multidimensional framework to understand psychopathology and guide associated research. Specifically, Harrison et al. (2019) argue that given the relevance of sensory processing (which includes sensory sensitivity, but additionally perceptual signalling or interoception) to a range of diagnoses, a sensory domain would be important in enhancing our understanding of mental health diagnoses using this framework. This initial suggestion focused on autism, anxiety, depression, and OCD, whilst chapters within this thesis considered a much broader range of conditions and areas of neurodiversity (although only some of which are relevant to RDoC). The common occurrence of

sensitivities across relevant conditions (detailed in Chapters 2, 3, and 7), and associated impact on wellbeing (detailed in Chapter 4) supports the need for further study and enhanced understanding of sensitivities, including integration with (or into) dimensional approaches such as RDoC.

To an extent, this requires moving beyond condition-centred study. In existing literature, theories surrounding the causes of sensitivities have arisen in relative (often condition-specific) isolation. For instance, causes and correlates of visual stress specifically have been investigated, with particular focus on these experiences in migraine, epilepsy, and dyslexia (e.g., Marcus & Soso, 1989; Wilkins, 2021), and associated excitability in visual cortex (e.g., Huang et al., 2011). Similarly, as a result of the centrality of sensory differences to autism, causal theories of cross-modal sensitivities have often been developed in the context of this diagnosis (e.g., see Robertson & Baron-Cohen, 2017) and subsequently extended to account for individual variability outside of autism (Ward, 2018). Theories are varied and include top-down accounts centring on prediction (Pellicano & Burr, 2012), as well as connectivity (Markram & Markram, 2010) or fundamental dysregulation (i.e., cortisol; Corbett et al., 2009). One of the clear theoretical outcomes of this thesis is that there is a need to bridge these literatures, removing diagnostic boundaries, to account for the transdiagnostic nature and multidimensional structure of sensory sensitivities we have defined.

Practical Implications

Practical implications of this work have been described throughout, and largely focus on a need to improve the experience of sensitivities to benefit wellbeing. There are two possible approaches to this.

The first involves adaptation to public environments. In Chapter 4, thematic analysis summarised how participants found the sensory aspects of public spaces challenging; environments included supermarkets, concerts, workplaces, and universities (e.g., lecture theatres). As well as affecting personal wellbeing, it is possible that avoidance of these settings (a described coping mechanism) could affect health or occupational achievement. Adjustments to public settings to improve their sensory impact can be relatively easy to implement. For instance, in a recent randomized crossover trial with autistic children, the effect of sensory

adaptations to a dentist were investigated (Duker et al., 2023). Modifications included a social story prior to the visit, reduction in overhead and directed lighting, and the addition of calming sensory stimuli if desired (sounds, tactile pressure, slow moving visual effects). In the adapted visit, children's overt and physiological distress was significantly reduced. This intervention was relatively inexpensive, highly scalable, and easy to implement, and the authors acknowledge its possible benefit to other groups, including those with high anxiety (Duker et al., 2023).

This is only one such example of sensory adaptations being proposed (Harris et al., 2023; MacLennan et al., 2022b; Waisman-Nitzan et al., 2021) or showing efficacy (e.g., Gupta et al., 2019). Although these examples are largely framed as being beneficial for autistic individuals, the work described in this thesis highlights the potential benefits of sensory adaptations for a range of individuals for whom sensory differences are impactful. Work described here could also provide initial insights into the most effective routes to sensory accommodations. For instance, adjustments which improve the nature of auditory, visual, and tactile input may have the most widespread benefit, given they were most commonly associated with aversive experiences (see Chapter 4). As well as introducing permanent changes in the built environment (e.g., to lighting, or to architecture), findings described in Chapter 4 suggest that increased control or predictability in sensory spaces might reduce aversive feelings.

Enhancing control or predictability may take different forms across public spaces. In occupational or educational environments, this could involve physical adaptations such as dimmer switches or adjustable blinds which allow the individual to define their optimal sensory input. However, it may also involve logistical adjustments including flexible or home working to allow greater control over the sensory environments and management of exacerbating factors (Petty et al., 2023). In healthcare or commercial settings, where individual control may not be possible, individualised adjustments could still be implemented; for instance, 'sensory pathways' (e.g., Gupta et al., 2019) which provide tools to help individuals cope (e.g., sensory toys, noise cancelling headphones), or sensory maps which can aid in predicting difficult sensory input (MacLennan et al., 2022b).

Alongside awareness of sensory sensitivities in public spaces, individual intervention may also be warranted where responses to sensory input are affecting wellbeing. There is limited evidence surrounding the efficacy of talking therapies for subjective sensitivities, although initial

evidence is promising; a cognitive behavioural therapy (CBT) based intervention for sensory differences in adolescents with autism has been reported to be feasible and acceptable (Edgington et al., 2016), and a randomized controlled trial found that CBT was effective in reducing hyperacusis (Jüris et al., 2014). Further study is needed in adults with cross-modal sensitivities and making use of active control groups (which were absent from Juris et al.), however. Other relevant, currently unstudied approaches could include acceptance and commitment therapy (ACT), or mindfulness based cognitive therapy (MBCT), whose tenets centre on acceptance and non-judgemental awareness of feelings. These are already delivered as intervention for many mood disorders (Alsubaie et al., 2017; Gloster et al., 2020), and thus could be extended to support aversive sensory experiences if necessary and proven efficacious.

In sum, results presented throughout this thesis suggest that improving support and intervention for sensory sensitivities is important for improving wellbeing and participation in social, functional, and occupational activities. Modality specific findings may be beneficial in informing the design of public spaces and the provision of sensory support (e.g., which stimuli are associated with positive sensory experiences), and increased sensitivities across clinical diagnoses and areas of neurodiversity suggests that sensory differences should be considered in clinical management where appropriate.

Limitations and Future Directions

All empirical chapters described have consistencies in methodology which require further discussion. For instance, each dataset was cross-sectional in nature, using self-report measures, and delivered online.

The inability to determine causal effects using cross-sectional research design has been acknowledged in previous chapters. For instance, work described in Chapters 2 and 7 established associations between anxiety symptoms and subjective sensitivities. As discussed, direction of effects is still yet to be determined, and future intervention studies will be particularly important in understanding these relationships (Green et al., 2012).

Regarding online recruitment, efforts were taken to diversify these samples, including recruiting from student populations, social media forums, the participant recruitment website Prolific, and community health list Health Wise Wales. However, a certain level of digital literacy,

resources, and access would still have been required to participate. This becomes particularly relevant to the findings if the sensory aspects of online surveys (e.g., bright screens, reading) or differences in wellbeing might preclude participation. Consideration of the nature and impact of subjective sensitivities, and of factors of visual sensitivity using the CHYPS-V, could therefore benefit from alternative recruitment and data collection methods in future study (e.g., focus groups, physical questionnaires).

Other considerations in this work surround the collection and analysis of data relating to clinical diagnoses and areas of neurodiversity. For instance, regression analyses used in Chapters 3 and 7 sought to understand how different conditions relate to subjective sensitivities. Specifically, all relevant diagnoses were included in a single regression model, to control for the influence of comorbid diagnoses. Although this is an approach used in existing empirical work (e.g., Bekhuis et al., 2015; Jain et al., 2018), how these statistical models relate to realistic clinical presentation should be considered. For instance, comorbidities are common and were frequent in our samples. There is therefore uncertainty surrounding the extent to which each diagnosis or area of neurodiversity is representative once the variance accounted for by comorbidities is removed.

As an example, as many as 70% of adults with ADHD have a comorbid diagnosis or area of neurodiversity (e.g., Piñeiro-Dieguez et al., 2016; Sobanski et al., 2007). The diagnosis of ADHD itself thus exists in the context of significant comorbidity. It is possible that controlling for a number of co-occurring diagnoses changes the conceptual nature of ADHD within the model, removing something fundamental about how the diagnosis presents. In other words, having ADHD without comorbidity is a minority situation, and thus controlling for comorbidity may lead the analysis to effectively base a correlation on an unusual feature of ADHD, not a representative essence of the diagnosis.

Further, it is known that individuals with comorbid diagnoses can have a different clinical profile than those without; for example, individuals diagnosed with both MDD and ADHD are known to report reduced quality of life compared to those without ADHD (McIntyre et al., 2010). Differing symptoms under conditions of comorbidity relates to an ongoing debate surrounding additivity and emergentism in clinical presentations (Petrolini & Vicente, 2022). In brief, whilst additivity would predict in an individual with both conditions A and B, symptoms of both

conditions would be present, emergentism in this context instead argues for unpredictability. That is, the interaction among condition A and B's symptoms may change the nature of the symptoms themselves, or lead to novel, emergent features of the specific intersection of diagnoses. This is further complicated by within condition heterogeneity (e.g., Fried & Nesse, 2015), which means that different symptom profiles (which fall under the same diagnosis) might interact with a comorbid condition in distinct ways.

Relating this to Chapters 3 and 7, the results of the regression analyses were largely (and reassuringly) consistent with theoretical and empirical work. However, these analyses should be interpreted in the context of their limitations; that is, subjective sensitivities might show more complex associations with clinical diagnoses under specific conditions of comorbidity which might have been masked by these analyses. For example, subjective sensitivities may be an emergent feature in individuals with a given combination of diagnoses or areas of neurodiversity (and potentially social or personality factors; Petrolini & Vicente, 2022), which are not captured by the regression model.

To develop a more nuanced understanding of how (and why) subjective sensitivities associate with clinical diagnoses and areas of neurodiversity, further study should move into transdiagnostic approaches which can acknowledge the effects of comorbidity. Stratification approaches such as the RDoC (Insel et al., 2010) and Hierarchical Taxonomy of Psychopathology (HiTOP; Kotov et al., 2017) are relevant here, which both seek to enhance understanding and research into clinical symptoms using distinct, but potentially complimentary (Michelini et al., 2021), dimensional approaches. For instance, in contrast to traditional classification approaches, the HiTOP is a hierarchically organized framework which conceptualizes psychopathology according to spectra which vary in severity (rather than the presence or absence of a categorical diagnosis). The ways in which subjective sensitivities relate to dimensions and domains (e.g., internalizing vs thought disorder) within these frameworks will be an important avenue for future work. This could be complimented by further network analyses, similar to those used in Chapter 7, which acknowledge that comorbid diagnoses may occur due to mutual interactions among symptoms (Fried et al., 2017). Consideration of how given symptoms, both transdiagnostic and condition specific, relate to each other and to subjective sensitivities may afford a more exact understanding of the relevance of sensitivities across clinical groups and comorbidities.

Diagnoses and areas of neurodiversity were also not confirmed in the samples used throughout this thesis; instead, participants self-reported their diagnosis or self-identification. This was felt to be warranted; formal diagnoses are difficult and time consuming to obtain, and would require access to primary care, or private healthcare in many cases (e.g., Young et al., 2021). Self-report or identification was therefore used to increase inclusivity and representativeness in the research, rather than limiting study to only participants for whom access to diagnoses is possible. Self-identification, and the reasons to do so, are also increasingly recognised (Overton et al., 2023), however symptom differences between those with formal and self-identified diagnoses appear to have not yet been studied. Investigation of the consistency of these findings in individuals with confirmed diagnoses will therefore be important.

Additionally, although specific participant groups were targeted via social media forums in Chapter 3, in the remaining chapters the conditions which were well powered enough to include in analyses were, for the most part, opportunistic. Although this is not problematic in terms of the findings, there are a number of diagnoses and areas of neurodiversity that could be theoretically relevant to sensory sensitivities but could not be investigated here. For instance, schizophrenia, bipolar disorder, substance related disorders, and borderline personality disorder have all been associated with increased subjective sensitivities (van den Boogert et al., 2022). Due to insufficient sample size, this work could not investigate the comparative nature or impact of sensitivities across these groups, although existing work does align with the findings presented here (e.g., increased auditory sensitivity in borderline personality disorder, as described in other diagnoses in Chapter 4). Similarly, sensory differences in some clinical groups remain largely unexplored, despite being comorbid with known correlates. For instance, a number of other personality disorders associate with anxiety disorders (Costache et al., 2020; Friborg et al., 2013) and with adverse experiences (Crișan et al., 2023), which are both known to co-occur with heightened subjective sensitivities (e.g., Serafini et al., 2016). Sensitivities would therefore be predicted to be increased in these groups; however empirical study is needed to confirm these differences.

Finally, much of this work was focused upon visual sensitivities specifically, and their multidimensional structure has been defined. Future work should seek to explore whether subtypes exist across other sensory modalities; for example, inputs known to cause auditory

sensitivities are varied, and uncomfortable sounds can vary from quiet to loud, high-pitched, repetitive, or overlapping (e.g., Landon et al., 2016). Similar issues with the measurement of these sensitivities exist for these stimuli, whereby multimodal measures of subjective sensitivities only assess some features (e.g., the AASP doesn't consider high-pitched, repetitive, or quiet sounds; Brown & Dunn, 2002), whilst measures which are more specific (e.g., misophonia; Rosenthal et al., 2021) are often used and studied in isolation. Theoretical understanding of auditory sensitivities, much like visual stress, also often focuses on the ear. For instance, some explanations of auditory sensitivities focus on differences in the semi-circular canals (e.g., Thabet, 2014). However, an aetiology centred on the ear does not explain why these sensitivities tend to associate with cross modal differences.

In order to develop unifying theory that can explain varied sensitivities which associate across sensory areas, future work must be both specific and broad in approach. Specific in identifying which forms of sensitivity a person is experiencing (e.g., within modality subtypes) and broad in considering how this relates to cross modal experience and thus mechanism. For example, it may be the case that subtypes of sensitivity which more readily associate with feelings of overwhelm (e.g., the IVE factor defined in Chapter 5, or multiple overlapping sounds; Landon et al., 2016) co-occur more often, and are more limbic in their origin as a result of the associated emotional response, when compared other forms of sensitivity. This is speculative at this stage but demonstrates how understanding subtypes of experience might enhance our understanding of aetiologies.

Summary

This thesis has investigated several important aspects of subjective sensory sensitivity, some of which are summarised by Figure 1.

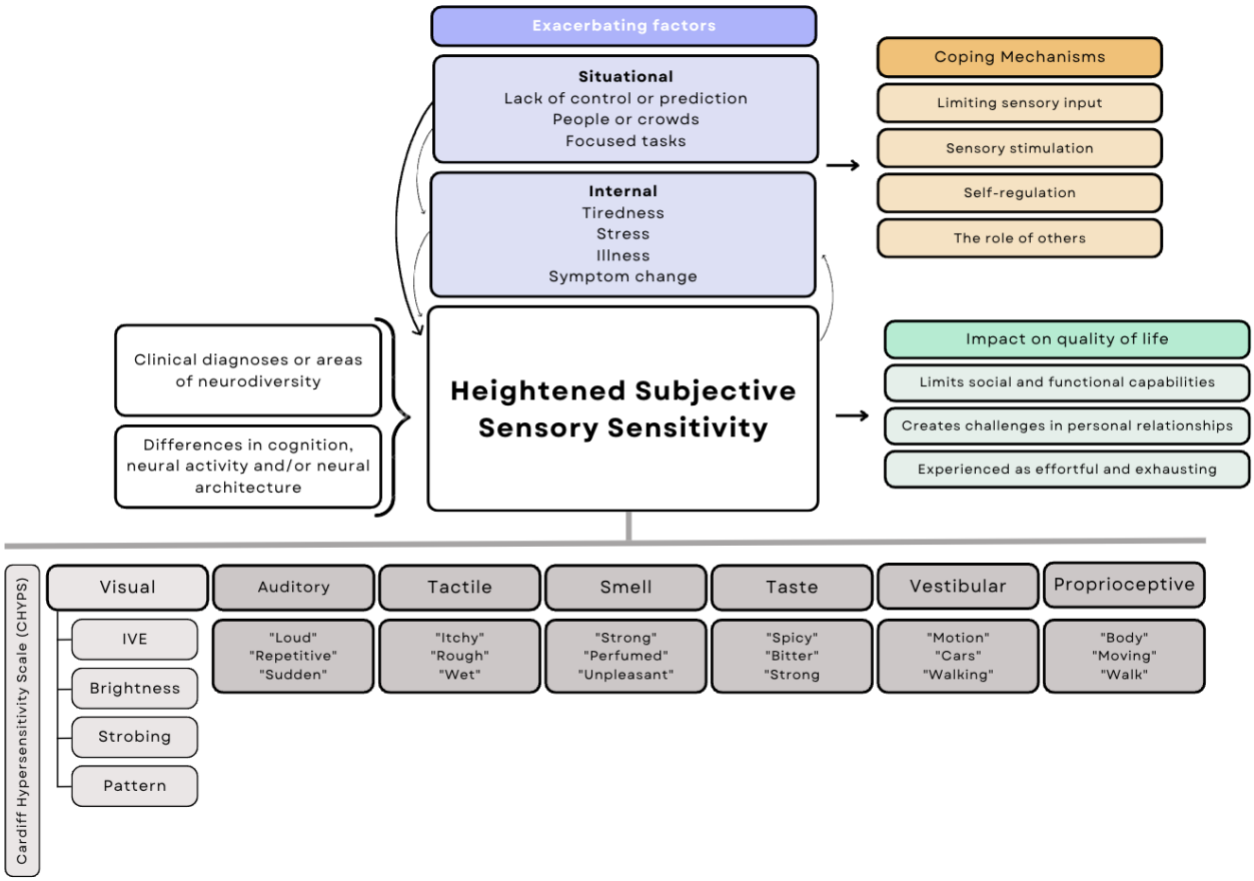


Figure 1. Schematic of findings, where purple, yellow and green boxes represent qualitative results, and grey boxes represent the current stage of CHYPS development. Words listed under each sensory heading were the most commonly used to describe the quality of aversive stimuli in that modality. *Note IVE = Intense Visual Environments.*

Although many have been discussed, three overarching implications are clear from this work. First, there is a need to transition beyond condition-specific study of subjective sensitivities, and instead move towards transdiagnostic or dimensional investigations. Sensitivities clearly associate with a range of conditions, which themselves exist in the context of comorbidity which should be acknowledged to enhance the specificity of future results. Second, the dimensionality of sensitivities in other sensory modalities should be considered (see grey

boxes in Figure 1). It is possible that by considering each modality as unidimensional, advancements in understanding of mechanisms are slowed, and individual differences are masked. Further iterations of the CHYPS-V across sensory modalities are therefore proposed. Finally, given the impact of sensitivities described by our participants, evidence-based and co-designed adjustments to public spaces should be implemented where possible. This requires involvement from both public sector and private enterprise, to ensure that accommodations are made across healthcare and educational settings, but additionally commercial and leisure environments. As described, adjustments can be low cost and scalable, and would have tangible and measurable benefit to those affected.

Several interesting and important questions also remain unanswered; a central question resulting from this work is what exactly is the unifying factor which means that individuals reporting a range of clinical diagnoses or areas of neurodiversity (which can be highly distinct in symptomology), or increased associated symptoms (e.g., anxiety) are more likely to experience subjective sensitivities. As discussed, it may be a simplification to assume a single common factor, given the diversity in theories of mechanisms described previously. However, consideration of how neural and subjective sensitivities relate, how sensitivities develop in concert with clinical symptoms (e.g., using longitudinal design), and how symptoms relate to and maintain each other (e.g., using network approaches) would be beneficial in beginning to unpack these complex relationships. Investigation of within subject differences relating to exacerbating factors defined here (e.g., stress, fatigue) may also provide important insight into mechanism.

In sum, this thesis has sought to combine novel statistical approaches with qualitative insights from a large number of participants to derive important conclusions surrounding the nature, impact, and measurement of subjective sensitivities. It is hoped that this work has provided initial foundations from which future studies, accommodations, and intervention can build.

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Appendices

Appendix A: Tables displaying clinical diagnoses and areas of neurodiversity reported by participants according to Chapter

Chapter 2

Condition or area of neurodiversity	*Frequency reported in sample (n = 944)*
Vestibular migraine	33
Labyrinthitis	13
Ménière's disease	11
Benign paroxysmal positional vertigo	27
Vestibular neuronitis	1
Stroke	2
Head trauma	2
Vestibular schwannoma	2

Chapter 3 and 4

Condition or area of neurodiversity	*Frequency reported in sample*	
	Chapter 3 (n = 578)	*Chapter 4 (n = 713)*
Attention Deficit Hyperactivity Disorder	74	89
Anorexia	37	50
Anxiety	232	284
Autism	56	68
Binge Eating Disorder	13	18
Bulimia	27	32
Depression	157	191
Dyslexia	21	30
Dyspraxia	5	4
Epilepsy	5	5
Fibromyalgia	5	8
Migraine	55	74
Obsessive Compulsive Disorder	45	50

Persistent Postural Perceptual Dizziness	14	20
Post-Traumatic Stress Disorder	35	42
Synaesthesia	28	39
Schizophrenia	3	6
Tourette's	10	11
Visual Stress	3	4
Other	30	42

Chapter 5

Condition or area of neurodiversity	*Frequency reported in sample*		
	Study 1: Prolific (n = 349)	*Study 1: University (n = 517)*	*Study 2: Prolific (n = 790)*
Attention Deficit Hyperactivity Disorder	22	55	98
Anorexia	11	36	16
Autism	36	26	77
Binge Eating Disorder	13	20	48
Bulimia	7	17	15
Depression	90	101	210
Dyslexia	14	30	43
Dyspraxia	12	4	23
Epilepsy	6	3	16
Fibromyalgia	10	3	27
Generalized Anxiety Disorder	55	135	169
Migraine	27	24	88
Obsessive Compulsive Disorder	26	30	56
Panic	17	29	44
Persistent Postural Perceptual Dizziness	7	5	25
Post-Traumatic Stress Disorder	25	20	73

Schizophrenia	6	2	10
Social	50	97	133
Synaesthesia	6	3	17
Tourette's	6	2	12
Visual Stress	7	5	10
Other	11	16	36

Chapter 6

Condition or area of neurodiversity	*Frequency reported in sample (n = 1133)*
Attention Deficit Hyperactivity Disorder	60
Anorexia	11
Autism	60
Binge Eating Disorder	21
Bulimia	7
Depression	212
Dyslexia	47
Dyspraxia	22
Epilepsy	9
Fibromyalgia	58
Generalized Anxiety Disorder	135
Migraine	242
Obsessive Compulsive Disorder	51
Panic	40
Persistent Postural Perceptual Dizziness	41
Post-Traumatic Stress Disorder	75
Schizophrenia	1
Social	93
Synaesthesia	12
Tourette's	3
Visual Stress	12
Other	102

Appendix B: Chapter 2 supplementary analyses

Mediation analysis with separate AASP subscales

Two mediation models were generated in the same manner as the main analyses in Chapter 2, instead including sensory sensitivity and sensory avoidance subscales as the independent variable.

In the first mediation analysis, we considered whether anxiety symptoms influenced the relationship between the sensory sensitivity subscale and migraine (Figure S1). The total effect of sensory sensitivity upon migraine was significant (c = .06, p < .001). The estimated indirect via anxiety was 0.03, and the 95% bootstrapped confidence interval was entirely above zero (0.01 to 0.04), and thus significant. The direct effect of sensory sensitivity upon migraine remained significant once this mediating effect was accounted for (c' = .04, p = .002), indicating partial mediation.

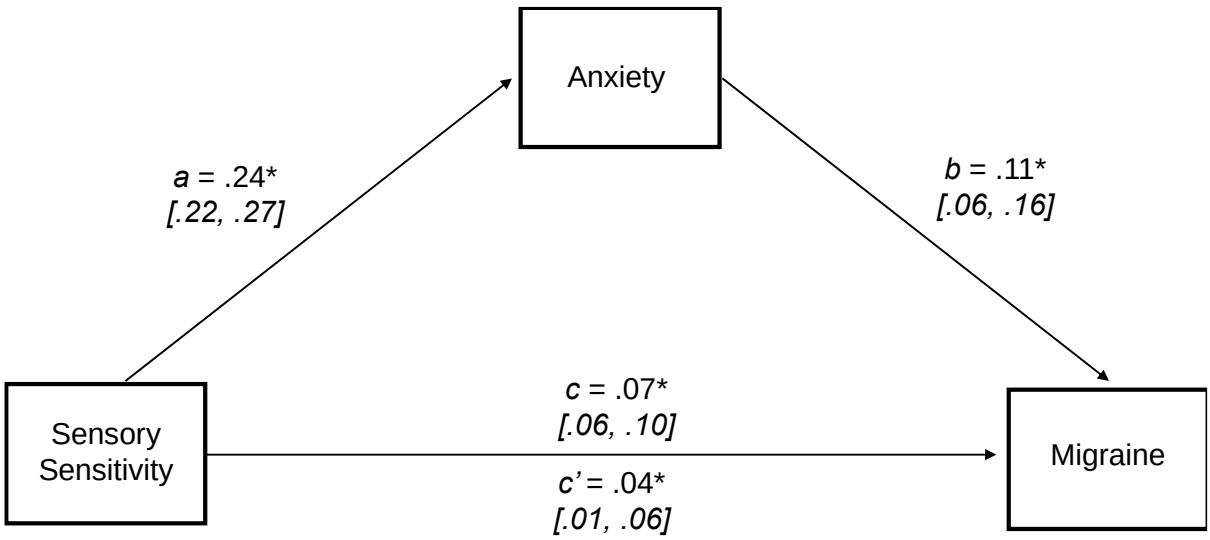


Figure S1 Mediation model of the relationship between sensory sensitivity, anxiety and migraine including 95% confidence intervals for each path. Each path denotes associations between variables of interest and are on a log-odds metric. *p < .005.

Similarly, the total effect of sensory avoidance upon migraine was significant (c = .06, p < .001). The indirect effect of anxiety was 0.02, which is also significant (0.01 to 0.04). The direct

effect of sensory avoidance upon migraine remained significant (c' = .04, p = .003). These effects are displayed in Figure S2 and suggest the presence of partial mediation.

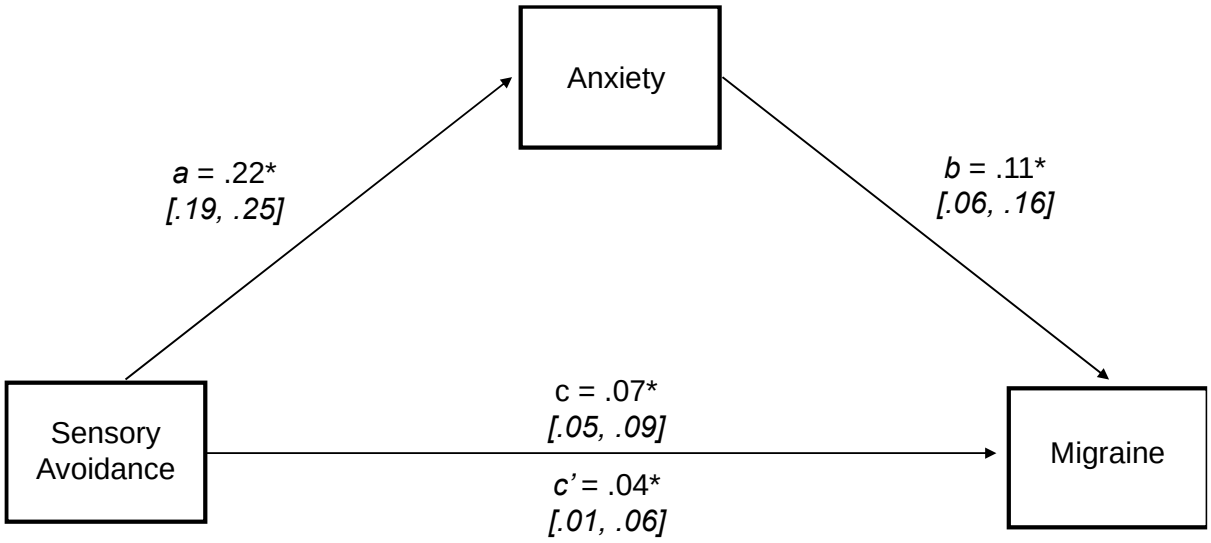


Figure S2 Mediation model of the relationship between sensory avoidance, anxiety and migraine including 95% confidence intervals for each path. Each path denotes associations between variables of interest and are on a log-odds metric. *p < .005.

To summarise, both sensory measures (sensory sensitivity and sensory avoidance) were significantly associated with migraine both directly, and via the mediating effect of anxiety symptoms.

Mediation analysis using depression symptoms

Given that anxiety was found to be a significant partial mediator in our initial analyses, it was of interest to determine whether depression symptoms similarly influenced the relationship between subjective sensory sensitivity and migraine.

Depression symptom scores in our participants with probable migraine are indeed significantly higher than our control sample (t (942) = 7.20, p < .001, d = 0.71), a known association in the literature. However, in a mediation analysis (covarying for age, gender and anxiety symptoms), depression was found not to mediate the relationship between sensory sensitivity and migraine (Indirect effect = .002, LLCI = -.003, UCLI = .006), supporting our hypothesis that

depression does not influence this relationship in our sample. These findings are summarised in Figure S3.

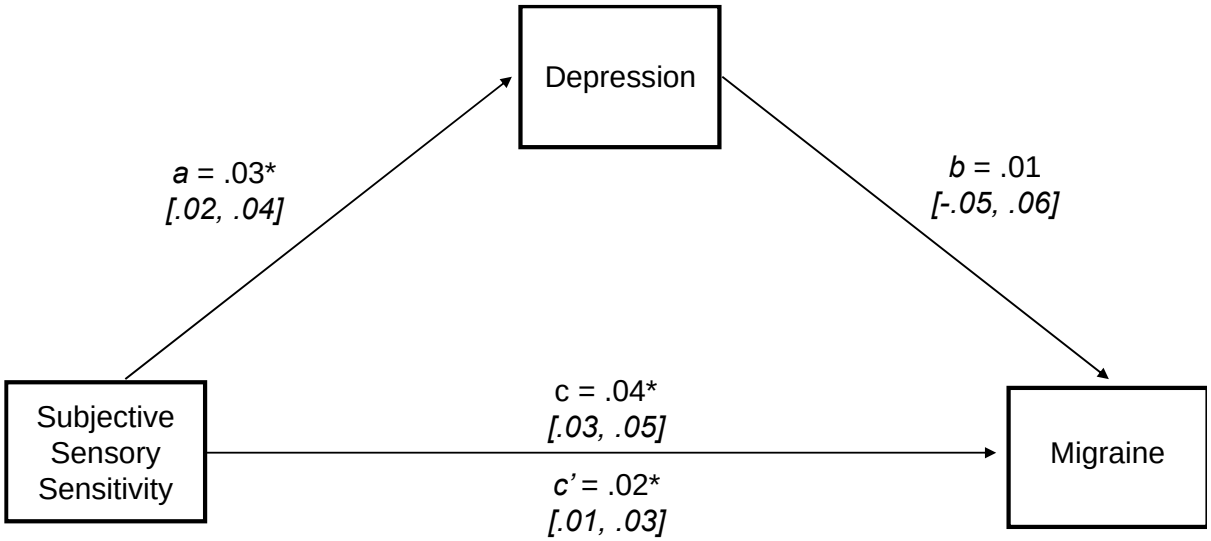


Figure S3 Mediation model of the relationship between subjective sensory sensitivity, depression and migraine including 95% confidence intervals for each path. Each path denotes associations between variables of interest and are on a log-odds metric. *p < .001.

Appendix C: Chapter 4 supplementary analyses

Figures S4 and S5 display content analyses calculated according to the number of participants reporting positive and negative sensory experiences in each modality. Results are consistent with the analyses which instead focus on instances, reported in Chapter 4.

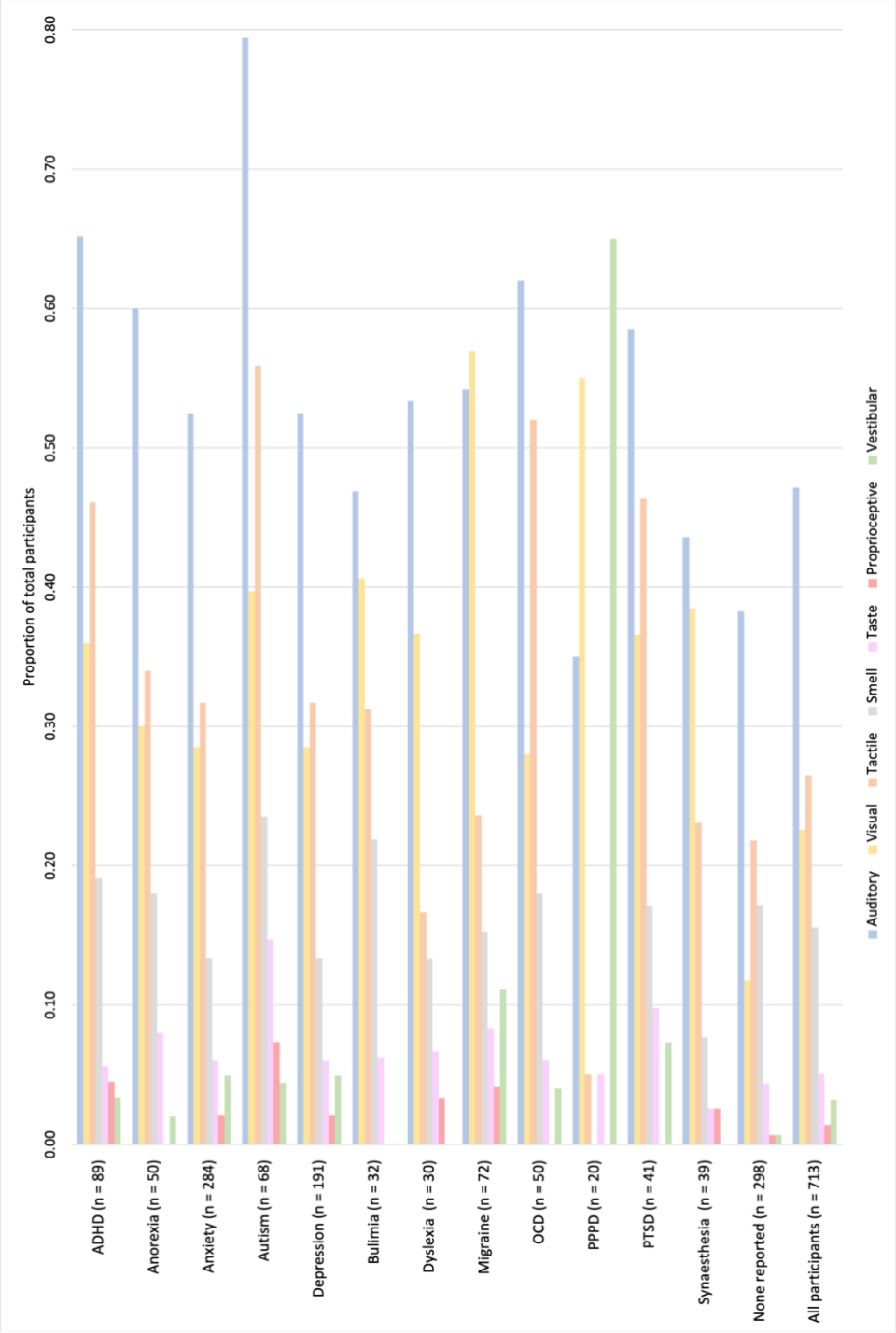


Figure S4. Proportion of participants reporting negative sensory experiences attributed to each sensory modality across individuals reporting clinical diagnoses and areas of neurodiversity, and those without, identified using content analysis.

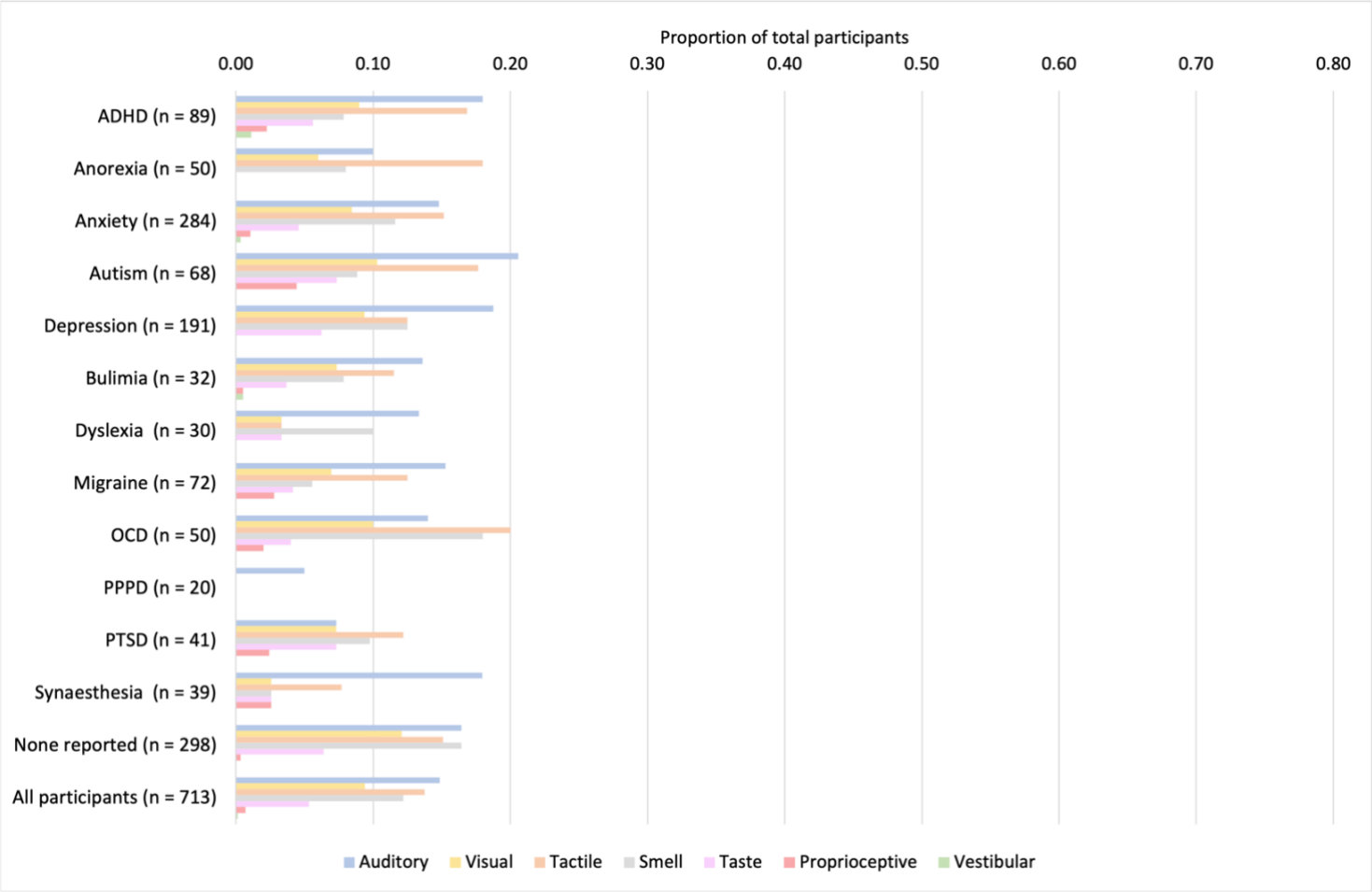


Figure S5. Proportion of participants reporting positive sensory experiences attributed to each sensory modality across individuals reporting clinical diagnoses and areas of neurodiversity, and those without, identified using content analysis.

Appendix D: CHYPS-v1 items, grouped by hypothesized and actual factors

Hypothesized factor	Item Brightness Strobing Pattern IVE
Brightness	I avoid watching TV in a dark room because I find the bright screen too uncomfortable to look at
	I tend to wear sunglasses or a hat outside on bright days, even if it is cloudy*
	Even if the sun is not directly in my eyes, I need to put the window shade down when driving in bright conditions because the light is uncomfortable for my eyes or head*
	Looking at bright lights in my environment triggers a headache*
	I find it uncomfortable for my eyes and head when driving through a tunnel with bright lights inside*
	I tend to use soft lamp lighting rather than bright ceiling lights at home, because I find it more comfortable for my eyes and head
	On a bright day, I get a headache when outside without sunglasses or a hat*
	I reduce the brightness on my devices with screens (e.g., by turning brightness down, using night mode, or dark settings) because otherwise I find them uncomfortable to look at
Pattern	Reading a book, magazine or newspaper makes my eyes feel sore, strained, dry, or achey
	Looking at repeating or stripy patterns (e.g., patterned flooring, wallpaper, buildings, striped clothing) makes my eyes or head feel so uncomfortable I need to look away from them*
	Stripey and repeating patterns and pictures seem to shimmer, flicker, or move when I look at them*
	Looking at repeating or stripey patterns triggers a headache*
	Going to cluttered shops or supermarkets triggers a headache*
	I try to avoid going to large or cluttered shops or supermarkets because I find them visually uncomfortable (e.g., too many objects, shelves, bright colours, and lights)*
Flicker	I avoid or move away from flickering lights or screens because they make my eyes or head feel uncomfortable*
	I close my eyes or look away if there are strobing or flashing lights on a TV programme or a film at the cinema*
	I find it uncomfortable for my eyes and head when travelling in a vehicle if sunlight is flickering in-between trees or buildings*
	I avoid going to venues (e.g., clubs, bars, theatres, concerts) if there are bright or strobing lights, in case they make my eyes or head feel uncomfortable*
	Flickering in my environment (e.g., lights flashing through trees, disco balls) triggers a headache*
	Flickering lights or screens triggers a headache*
Motion	I avoid watching TV, films, or media that have a lot of motion (e.g. camera panning, car chases, lots of objects moving fast in the scene, shaky camera footage), because I find them uncomfortable to look at*
	Watching TV, films, or media that have a lot of motion (e.g. camera panning, car chases, lots of objects moving fast in the scene, shaky camera footage) triggers a headache
	Seeing too many moving objects in my surroundings (e.g., moving traffic, crowds of people moving around) triggers a headache*
	Looking at a screen scrolling on a phone or computer makes me want to look away

	I find everyday environments with a lot of movement (e.g., busy traffic passing by, crowds of people moving around) uncomfortable for my eyes and head*
	I find it uncomfortable for my eyes and head when objects are moving in the corner of my eye*

*Items which were retained in the final factor solution in Study 1. These items are colour coded according to which factor they were associated with in the final factor model, where yellow = Brightness, red = Strobing, green = Pattern, blue = Intense Visual Environments. *Note* – solutions differed across samples. Items are coloured if they formed part of a factor in either sample.

Qualitative questions included to integrate participant feedback in the measure's development:

- *Were any of the questions listed above unclear or difficult to understand? If so, please give details below:*

- *Do you find yourself having to cope with or manage your reactions to any of the situations listed above? In what ways do they impact your day-to-day life, if at all?*

- *Can you provide any other examples of particular types of visual stimuli, scenarios, or environments, not listed above, that you find uncomfortable for your eyes or head:*

Appendix E: CHYPS-v2 items, grouped by hypothesized and actual factors

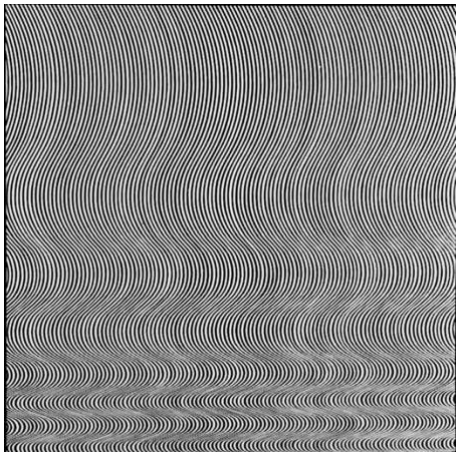
Hypothesized factor	Item Brightness Strobing Pattern IVE
Brightness	I tend to wear sunglasses or a hat outside on bright days, even if it is cloudy
	Even if the sun is not directly in my eyes, I need to put the window shade down when driving in bright conditions because the light is uncomfortable for my eyes or head*
	On a bright day, I get a headache when outside without sunglasses or a hat
	Looking at bright lights in my environment triggers a headache
	I try to avoid places or rooms with bright lights in case they make my eyes or head feel uncomfortable
	I turn off or dim bright ceiling lights because they make my eyes or head feel uncomfortable*
	When sunlight is reflected off surfaces (e.g., water, snow, mirrors, cars, screens) it makes my eyes or head feel so uncomfortable that I need to look away*
	My eyes or head feel uncomfortable if there is a bright light in the dark (e.g., cinema screens, lecture theatres, torches, car headlights at night)
	I find sudden changes from dark to light highly uncomfortable for my eyes and head (e.g., turning on lights at night, coming out of a dark room)*
Pattern	Looking at repeating or stripy patterns (e.g., patterned flooring, wallpaper, buildings, striped clothing) makes my eyes or head feel so uncomfortable I need to look away from them*
	Stripey and repeating patterns and pictures seem to shimmer, flicker, or move when I look at them*
	Looking at repeating or stripey patterns triggers a headache
	When there are lots of bright colours around me, I tend to get a headache*
	I try to avoid looking at neon, bright, or contrasting colours because they are uncomfortable for my eyes or head
	Looking at black text or patterns on white backgrounds makes my eyes or head feel uncomfortable
	I need to look away from or avoid complex patterns in my environment (e.g., wallpaper, carpets, artwork)*
	I find rooms or buildings with stripy or complex features (e.g., high contrast panelling, brickwork, columns) uncomfortable to look at*
	Clothing with stripes, checks, or complex patterns make me want to look away*
Intense visual environments (IVE)	Going to supermarkets triggers a headache
	I try to avoid going to supermarkets because I find them visually uncomfortable (e.g., too many objects, shelves, bright colours, and lights)*
	I find everyday environments with a lot of movement uncomfortable for my eyes and head*
	Seeing too many moving objects in my surroundings triggers a headache
	I avoid going to fairgrounds or theme parks because the visual stimulation is uncomfortable or gives me a headache
	Cluttered or visually disorganized places (e.g., rooms, shops or other environments) make my eyes or head feel uncomfortable
Flicker	I avoid or move away from flickering lights because they make my eyes or head feel uncomfortable
	I close my eyes or look away if there are strobing or flashing lights on a TV programme or a film at the cinema*
	Flickering in my environment (e.g., lights flashing through trees, disco lights) triggers a headache
	Flickering lights or screens triggers a headache
	I find it uncomfortable for my eyes and head when travelling in a vehicle if sunlight is flickering through the window, such as in-between trees or buildings*
	I try to avoid venues where there will be strobing or flashing lights (e.g., clubs, theatres, concerts) in case they make my eyes or head feel uncomfortable
	Flickering screens are uncomfortable for my eyes and head

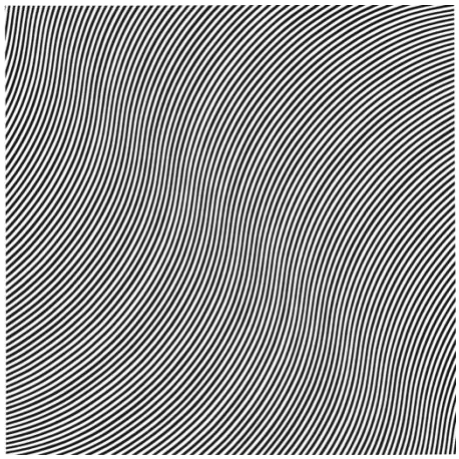
	I find it uncomfortable for my eyes and head when lights are quickly moving past me (e.g., when driving through a tunnel)
Motion	I try to avoid watching films or TV which have lots of fast movements or uses shaky camera footage (e.g., sports games, action films) because I find them uncomfortable to look at
	I find it uncomfortable for my eyes and head when objects are moving in the corner of my eye
	I look away if things are rotating or spinning in circles, because it makes my eyes or head feel uncomfortable
	I do not look out of the window in a moving train or vehicle, because otherwise it makes my eyes or head feel uncomfortable
	Video games with lots of motion make my eyes or head feel uncomfortable
	I have to look away when watching sports or people running and moving around quickly because it's visually uncomfortable
	Watching crowds of people moving around is uncomfortable for my eyes and head
	I find busy and fast-moving traffic uncomfortable to look at
	Seeing too much motion and movement on a screen (e.g., cinema, TV, video games) triggers a headache

*Items which were retained in the final bifactor solution in Study 2. These items are colour coded according to which factor they were associated with in the final bifactor model, where yellow = Brightness, red = Strobing, green = Pattern, blue = Intense Visual Environments.

Appendix F: Discomfort images and rating scales

Three images shown to participants during Study 2:





Participants used the following rating scales to indicate their discomfort in response to the images:

1. Which of these statements best describes how you feel about this image:
    - I find this image so uncomfortable to look at I would need to look away immediately
    - I find this image uncomfortable to look at but could tolerate it for very short periods
    - I find this image a bit uncomfortable, but could tolerate it as a poster if I was sitting opposite it in a café
    - This image is comfortable enough to look at that it could be hung up as a poster in my home
    - This image is comfortable enough that I could live in a house where it had been used to wallpaper the living room

2. Based on how comfortable it is to look at, how long would you be willing at look at this image for?
    - I immediately have to look away from this image
    - I could look at it for 5 seconds
    - I could look at it for 1 minute
    - I could look at it for 5 minutes or more

Appendix G: Convergent and divergent validity of CHYPS-v2 subscales

Correlations between CHYPS-v2 subscales and convergent validity measures are shown in Table 1. Moderate correlations were found with all subscales, with the strongest correlations found between PPPD symptom measures VVAS and Niigata and the CHYPS-v2 IVE factor. Correlations between CHYPS-v2 subscales and ratings in response to the three discomfort images were also moderate. Although largely similar, the greatest correlation was evident with the Pattern subscale, which is intuitive in terms of this subscale's content. All correlations were significant ($p < .001$).

Table 2 displays correlations between CHYPS-v2 subscales and divergent validity measures, represented by the O-life. Weaker correlations were evident for Impulsive Non-conformity and Introvertive Anhedonia subscales of the O-Life. Similar to the CHYPS total score, Cognitive Disorganisation and Unusual Experiences subscales showed comparatively increased correlations, however less so for the Strobing subscale. All correlations were significant ($p < .05$).

	MSQ	VVAS	Niigata	Average time	Average comfort
Pattern	0.35	0.55	0.47	0.46	0.49
Brightness	0.43	0.49	0.47	0.40	0.44
Strobing	0.34	0.54	0.50	0.39	0.41
IVE	0.38	0.60	0.54	0.38	0.39

Table S1. Spearman correlations between CHYPS-v2 subscales and validity measures (MSQ and O-Life subscales). *Df:* MSQ, VVAS, Niigata = 777, *Df* Average time, Average comfort = 763. *Note. IVE = intense visual environments, VVAS = Visual Vertigo Analogue Scale, MSQ = Migraine Screening Questionnaire. Average time = averaged response to time willing to spend looking at the image (See Appendix F), Average comfort = comfort rating in response to the image (See Appendix F).*

	Cognitive Disorganisation	Introvertive Anhedonia	Impulsive Non-conformity	Unusual experiences
Pattern	0.35	0.21	0.19	0.34
Brightness	0.40	0.20	0.17	0.33
Strobing	0.26	0.21	0.10	0.25
IVE	0.37	0.21	0.27	0.38

Table S2. Spearman correlations between CHYPS-v2 subscales and O-Life subscales. *Df* O-life subscales = 646. *Note. IVE = intense visual environments, O-Life = Oxford-Liverpool Inventory of Feelings and Experiences.*

Appendix H: The Cardiff Hypersensitivity Scale (Visual)

This questionnaire asks about whether situations are comfortable or uncomfortable for your eyes and head. Although a situation might be uncomfortable because it is upsetting, frightening, or disgusting, this is not what we mean.

We are asking specifically about whether these situations are **physically uncomfortable**, causing some form of **physical pain, tiredness, ache, or strain in or around your eyes or head.**

Please answer each question based on what happens when you experience a given situation, rather than how often you experience it. For example, if you always experience discomfort when ironing a stripey shirt, but don't often iron them, you should respond 'Almost Always'.

Please indicate what we mean by 'uncomfortable' in the questions you are about to answer (please read the text above if you are not sure):

- ○ Upsetting
- ○ Frightening
- ○ Disgusting
- ○ Physical pain, tiredness, or strain in or around your eyes or head

---

This questionnaire asks about whether situations are comfortable or uncomfortable for your eyes and head. Although a situation might be uncomfortable because it is upsetting, frightening, or disgusting, this is not what we mean.

We are asking specifically about whether these situations are **physically uncomfortable**, causing some form of **physical pain, tiredness, ache, or strain in or around your eyes or head.**

Please answer each question based on what happens when you experience a given situation, rather than how often you experience it. For example, if you always experience discomfort when ironing a stripey shirt, but don't often iron them, you should respond 'Almost Always'.

---

1. When I look at repeating or stripy patterns (e.g., patterned flooring, wallpaper, buildings, striped clothing), it makes my eyes or head feel so uncomfortable I need to look away from them

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

2. I try to avoid watching films or TV which have lots of fast movements or uses shaky camera footage (e.g., sports games, action films) because I find them uncomfortable to look at

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

3. I find it uncomfortable for my eyes and head when travelling in a vehicle if sunlight is flickering through the window, such as in-between trees or buildings

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

4. I find everyday environments with a lot of movement uncomfortable for my eyes and head

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

5. Stripy and repeating patterns and pictures seem to shimmer, flicker, or move when I look at them

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

6. I close my eyes or look away if there are strobing or flashing lights on a TV programme or a film at the cinema

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

7. Even if the sun is not directly in my eyes, I need to put the window shade down when driving in bright conditions because the light is uncomfortable for my eyes or head

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

8. When there are lots of bright colours around me, I tend to get a headache

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

9. I turn off or dim bright ceiling lights because they make my eyes or head feel uncomfortable

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

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10. Video games with lots of motion make my eyes or head feel uncomfortable

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

11. Cluttered or visually disorganized places (e.g., rooms, shops or other environments) make my eyes or head feel uncomfortable

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

12. I need to look away from or avoid complex patterns in my environment (e.g., wallpaper, carpets, artwork)

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

13. Watching crowds of people moving around is uncomfortable for my eyes and head

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

14. When sunlight is reflected off surfaces (e.g., water, snow, mirrors, cars, screens) it makes my eyes or head feel so uncomfortable that I need to look away

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

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15. I find rooms or buildings with stripy or complex features (e.g., high contrast panelling, brickwork, columns) uncomfortable to look at

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

16. Seeing too much motion and movement on a screen (e.g., cinema, TV, video games) triggers a headache

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

17. I try to avoid going to supermarkets because I find them visually uncomfortable (e.g., too many objects, shelves, bright colours, and lights)

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

18. I try to avoid venues where there will be strobing or flashing lights (e.g., clubs, theatres, concerts) in case they make my eyes or head feel uncomfortable

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

19. I find sudden changes from dark to light highly uncomfortable for my eyes and head (e.g., turning on lights at night, coming out of a dark room)

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

---

20. Clothing with stripes, checks, or complex patterns make me want to look away

- ○ Almost Never
- ○ Occasionally
- ○ Often
- ○ Almost Always

Scoring

- Responses are scored on a scale from 0-3.

- A total score can be calculated as a sum.

- Separate sum scores can also be calculated for the following subscales:
  Pattern: items 1, 5, 12, 15, 20
  Strobing: items 2, 6, 10, 16, 18
  Brightness: items 3, 7, 9, 14, 19
  Intense Visual Environments: items 4, 8, 11, 13, 17