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Understanding the subtypes of visual hypersensitivity: Four coherent factors and their measurement with the Cardiff Hypersensitivity Scale (CHYPS)☆

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ABSTRACT

Subjective visual sensitivity or discomfort has been reported in many separate literatures, and includes a wide range of visual triggers (e.g., repeating patterns, bright lights, motion, flicker) across a wide range of neurological, psychiatric, mental health, and developmental conditions and areas of neurodiversity (e.g., migraine, traumatic brain injury, functional neurological disorder, PPPD, PTSD, anxiety, depression, anorexia, OCD, autism, ADHD, dyslexia, dyspraxia, synaesthesia). To unite this research across disciplines and to allow progress in mechanistic understanding, we aimed to provide a definitive answer to whether there are different subtypes (factors) of visual hypersensitivity. In Study 1, we generated questions from a large qualitative dataset (n = 765), existing literatures, questionnaires, and iteratively from participant feedback. We found four theoretically coherent factors replicated across five cohorts (n's = 349, 517, 349, 417, 797 and 1817). These factors were: brightness (e.g., sunlight), repeating patterns (e.g., stripes), strobing (e.g., flashing, screen motion), and intense visual environments (e.g., supermarkets, traffic). There was also a general factor. Based on this we produced a novel 20-item questionnaire (the Cardiff Hypersensitivity Scale, CHYPS), with good reliability ($\alpha > 0.8$, $\omega > 0.8$) and convergent validity (correlations with other visual scales $r > 0.6$). We discuss how these factors can be related to causal theories of hypersensitivity.

1. Introduction

Visual hypersensitivity or discomfort refers to first person (subjective) reports of experiencing visual stimuli as aversive, uncomfortable, or overwhelming (Ward, 2019). Importantly, it is an experience generated by supra-threshold sensory input and does not generally correlate with detection ability in psychophysical tasks (Schulz & Stevenson, 2021; Ward, 2019). Therefore, research relies largely on self-report. Heightened subjective visual sensitivity is relatively common in the general population (Robertson & Simmons, 2013), and has been studied extensively in connection with migraine (Price et al., 2021; Wilkins et al., 2021), dyslexia (Estaki et al., 2021), and autism (Parmar et al., 2021), for example. Visual hypersensitivity has also been reported across a very wide range of other neurological, psychiatric and neurodevelopmental conditions and areas of neurodiversity (and trait questionnaires for related characteristics), including attention deficit hyperactivity disorder (ADHD; Bijlenga et al., 2017), anorexia (Bell et al., 2017; Zucker et al., 2013), anxiety (Digre & Brennan, 2012), Avoidant/Restrictive Food Intake Disorder (ARFID; Dovey, Kumari, & Blissett, 2019; Pilato, 2021), bulimia (Bell et al., 2017), depression (Qi et al., 2019; Digre & Brennan, 2012), epilepsy (Shahar et al., 2013), fibroymyalgia (Brink & Bultitude, 2022; Wilbarger & Cook, 2011), functional neurological disorder (Ranford et al., 2020), persistent postural perceptual dizziness (PPPD; Powell et al., 2020b; Powell et al., 2021), post-traumatic stress disorder (PTSD; Engel-Yeger et al., 2013), synaesthesia (Ward et al., 2017), Tourette's syndrome (Ludlow & Wilkins, 2016), and traumatic brain injury (Callahan et al., 2018). As such, visual hypersensitivity has a role in predicting and understanding brain development, mental health outcomes, and neurological rehabilitation and occupational therapy (e.g. Allen & Casey, 2017; Dowdy, Estes, Linkugel, & Dvornak, 2020; Engel-Yeger, Palgy-Levin, & Lev-Wiesel, 2013; Hui et al., 2022).

However, it is not yet clear whether there is one kind of visual hypersensitivity or several. Differences in methods and theoretical

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perspectives between disciplines, and the wide range of visual triggers reported, mean that it remains unclear whether the same phenomenon is being described in all disciplines and individuals. If there are dissociable types of sensitivity, these may have distinct mechanistic explanations and may be differentially exacerbated in different neurodevelopmental, neurological, psychiatric, and mental health conditions or areas of neurodivergence. On the other hand, a single construct of trans-diagnostic hypersensitivity would lead us to ask what common neural vulnerability could manifest across, or be a risk factor for, such a range of associated conditions and traits. Therefore, progress in both mechanistic and practical understanding depends upon knowing what types of visual hypersensitivity there are.

A dissociation between two major types of visual hypersensitivity might be predicted from the two main approaches to current causal theories. One theoretical framework focusses on visual cortex and stimuli that deviate from natural scenes statistics. In brief, sensory cortices are thought to favour sparse coding and be vulnerable to over-excitement by stimuli that deviate from natural properties, and for some people this vulnerability is enhanced (for reasons unknown) developmentally or due to brain trauma, for example (see Wilkins, 2025 and Ward, 2019 for reviews).

Other theoretical frameworks emphasise influences on perceptual experience from outside the visual system itself, such as emotional regulation, arousal, defence mechanisms and hypervigilance (Aron & Aron, 1997; Fleming et al., 2024; Green & Ben-Sasson, 2010; Greven et al., 2019). In these domains, sensory sensitivity has been discussed as a generic phenomenon (rather than in terms of specific stimulus features or scene statistics), with some emphasis on overwhelm to cluttered and complex environments.

Thus, two fundamental questions are raised: is there an important distinction between visual sensitivities that have an explanation in visual cortex processing, and more generalised sensitivities with broader underpinning in attentional, emotional, and arousal networks? And if (some) visual hypersensitivities have their source in visual cortices, are there dissociable types that align with the characteristics of different areas of visual cortex? If either or both hypotheses are true, factor analysis of the wide range of triggering stimuli and environments should identify different subtypes of hypersensitivity.

Data from previous research cannot answer these questions. Some existing questionnaires or tests have covered different aspects of visual sensitivity with a specific focus, such as photophobia (Bossini et al., 2006, 2009; Cortez et al., 2019, 2023), reading (Conlon et al., 1999), pattern glare (Evans & Stevenson, 2008; Wilkins, 1995) or bright or flickering lights and patterns (Perenboom et al., 2018). More general sensory questionnaires cover limited aversive triggers due to also covering other concepts such as hyposensitivity or sensation seeking (e.g., Brown & Dunn, 2002; Robertson & Simmons, 2013), and sometimes conflate aversive hypersensitivity with questions about detection.

Suggestive of dissociable factors are hints that discomfort ratings to pattern stimuli do not always correlate with questionnaires that do not include pattern questions (e.g., Glasgow Sensory Questionnaire; Roberston & Simmons, 2013; Ward et al., 2017). Further, in qualitative reports participants report varied triggers that may imply subtypes (e.g., Parmar et al., 2021). For instance, individuals reporting high levels of light sensitivity may not mention repeating patterns (and vice versa), but we do not know if this is just due to small relative differences in what is most salient to different people. On the other hand, some authors have concluded that visual hypersensitivity is a unidimensional construct (Aykan et al., 2020), but their work did not cover all visual triggers reported across the literature (e.g., no questions about pattern or cluttered environments).

Therefore, in this paper we elucidate the factor structure of visual hypersensitivity. To do so, we iteratively developed questions aiming to cover the full range of triggers based both on current visual sensitivity questionnaires and on qualitative reports. Having replicated a four-factor structure five times across three different types of cohort, we hone the items into a 20-item questionnaire (now referred to as the *Cardiff Hypersensitivity Scale*; CHYPS), in order to provide a unifying approach for future research.

Study 1. Factor structure for 26 items

2. Methods

2.1. Item development

We developed the initial 26 items for the measure based on three types of source:

The types of features in previous questionnaires for aspects of visual hypersensitivity: e.g., the Pattern Glare Test (Evans & Stevenson, 2008; Wilkins, 1995), the Photosensitivity Assessment questionnaire (Bossini et al., 2006; Bossini et al., 2009), the Adolescent/Adult Sensory Profile (AASP; Brown & Dunn, 2002), the Glasgow Sensory Questionnaire (GSQ; Robertson & Simmons, 2013), the Sensory Sensitivity Scales (SeSS; Aykan et al., 2020).

Wider insights about triggers in the literature, which indicated stripes, supermarkets (Popkirov et al., 2018; Robertson & Simmons, 2015; Wilkins, 1995), 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 films; Parmar et al., 2021; Ujike et al., 2008).

A new qualitative dataset (n = 765; Price, 2023) that 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 developed (see Sup. Table S1).

This resulted in 26 items (see *Sup. Table S2*), which were worded according to the following principles:

1. Wording focused on functional changes as a result of sensitivity (e.g., avoidance) rather than affective changes (e.g., dislike). 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. Therefore, in questions where it seemed reasonably possible to do so (without compromising clarity and brevity), we asked about frequency of avoidance or coping behaviours (e.g., needing to wear sunglasses on a bright day, needing to leave a certain situation). Similar approaches have been used previously (Aykan et al., 2020).
2. Given many circumstances known to trigger visual sensitivity may also be challenging for individuals with anxiety (e.g., supermarkets, crowds), we attempted to clarify that responses should be based on experiences of visual hypersensitivity (e.g., *"…because I find them visually uncomfortable"*).
3. We avoided priming language where possible (e.g., *"ceiling lights are too bright" vs "I use soft lamp lighting…")*.

Items were reviewed iteratively by members of the research team and collaborators within and beyond the field, to ensure readability and interpretability. The Flesch-Kincaid reading level for the item set was 80.2 ("Easy to read"; Flesch, 1948). Lastly, we requested qualitative participant feedback with two questions: *Were any of the questions listed above unclear or difficult to understand? If so, please give details below; 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?*

All items used a 4-point Likert frequency scale (0 = Almost Never, 1 = Occasionally, 2 = Often, 3 = Almost Always). All questions were delivered online via Qualtrics survey, and we also collected demographic information. Cardiff University's School of Psychology ethics committee provided ethical approval for all procedures.

2.2. Participants

Two samples were recruited to assess consistency of factor structure across groups. The first sample were 525 students at Cardiff University, who completed the online survey in exchange for course credit. The second were 350 participants recruited through the online research platform Prolific (https://prolific.co), using the representative sample function to recruit a cohort reflecting the demographic distribution of the UK population in age, sex and ethnicity (using data from the UK Office of National Statistics). Nine participants from the University sample and one from Prolific did not provide complete data and were therefore removed. Mean age was 46 (SD = 19.6) in the Prolific sample and 20 (SD = 2.8) in the university sample. In the University sample, 84.7 % reported female gender, 12.6 % male, and 2.3 % non-binary. In the Prolific sample, 51.6 % reported themselves as female, 47.6 % as male, and 0.9 % as non-binary. Informed consent was obtained from all participants, and experiments were carried out in accordance with the World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects.

2.3. 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, 2024) 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 (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., 2017; 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 0.30 (Costello & Osborne, 2005), and cross loadings were absent or had a difference of greater than 0.15 between factors (Worthington & Whittaker, 2006).

3. Results

3.1. Factor structure

Two models were identified as optimal, depending on criteria and cohort: the bifactor model with four specific factors, or the four-factor correlated factor model (fit statistics for all assessed models are displayed in *Sup.Table S3*). Thus, a four-factor solution was found in both samples, with a high degree of conceptual overlap across samples (Table 1). These factors were interpreted as sensitivity to Brightness, Pattern, Strobing, and Intense Visual Environments. In Table 1, we present these factors for the correlated factor model because in the bifactor solutions for both cohorts, some factor loadings fell below 0.3 (due to variance accounted for by the general factor), and the removal of these items would result in weak factors given we only had 26 items (Costello & Osborne, 2005). 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 University sample. Mean scores, reliability, and correlations between factors are reported in *Sup. Table S4*. Reliability as measured by α and ω was acceptable in all subscale and total scores. Subscale correlations were largely similar in magnitude across participant groups and did not suggest factor redundancy. In both samples, items associated with the Brightness and Strobing factors were most commonly endorsed, and IVE items the least.

Table 1
Factor loadings for Prolific (n = 349) and University (n = 516) samples, resulting from exploratory factor analysis (parallel analysis, oblimin rotation). *IVE = Intense Visual Environments. See Supplementary Table S2 for full item wording; (H) indicates that the item asked whether the stimuli triggered a headache.* Table shows strength of factor loadings across items of the questionnaire. Item loadings group together according to four factors. All factor loadings greater than 0.40.

Item	Brightness		Pattern		Strobing/Motion		IVE	
	Prolific	University	Prolific	University	Prolific	University	Prolific	University
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						
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					
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		
Supermarkets							0.82	0.68
Supermarkets (H)							0.78	0.69
High motion environments							0.51	0.69
Moving objects (H)								0.56

3.2. Qualitative responses

Participants across both samples (n = 866) were asked to provide feedback on the items' interpretability and completeness. No participant indicated that any of the items were unclear or difficult to understand. A very small minority (n = 3) reported some repetitive wording. In terms of completeness, 347 participants across both samples provided examples of visual stimuli they found uncomfortable that were not explicitly included in the 26 questions. These responses were manually collated into common themes, which broadly included: glare (e.g., light reflecting off water), contrasts in brightness (e.g., headlights at night, moving from dark to light), movement (e.g., motion associated with first-person video games), and colour (e.g., too much colour at once).

4. Discussion

Study 1 showed evidence of a theoretically sound four-factor structure and good reliability across two samples. However, specific item loadings were not always consonant, and the data may be limited by missing triggers and too few items. There may also be considerations for possible item confusion; for instance, the item *"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"* may create conflict between individuals sensitive to brightness (i.e., screens) and those sensitive to flicker (which can be introduced by pulse width modulation which is often the mechanism through which screen brightness is reduced; e.g., Laycox et al., 2024).

Study 2. Factor structure for 42 items

4.1. Item development

Additional questions were developed from participant feedback from the initial two cohorts, including the addition of items which covered triggers participants felt were absent, to enhance content validity. Items were also revised or split through reflection by the wider research team on possible interpretation ambiguities (e.g., where a question gave examples that might differ in key features, such as crowds and traffic; see *Supplementary Material B* (Fig. S1) for schematic of item development). This revision process resulted in 42 items, which are provided in *Sup. Table S5*.

In order to test this set, we initially recruited a student sample (*Cohort 3*, n = 417). Results showed four factors that were consistent with those in Table 1 (see *Sup. Table S6*). We then proceeded to test two larger and different cohorts (*Cohorts 4 and 5, below*) with these 42 items and a set of existing questionnaires for convergent validity.

4.2. Cohort 4

The online research platform Prolific was used to recruit 797 participants, representative for UK age, sex and ethnicity as identified by the UK Office of National Statistics, and to exceed the proposed ratio of 1:10 between scale items and respondents (Nunnally & Bernstein, 1994). Participants were compensated (£4.18) upon completion. Thirteen participants were removed from analysis for responding incorrectly to simple checks of attention and/or comprehension. Ten participants were removed due to missing data.

Of 774 participants, 48.7 % identified as male, 50.1 % as female, and 1.2 % as another gender identity. Mean age was 45.8 (SD = 15.6), with a range of 18–88. Reported ethnicities were: White (87 %), Black (3.2 %), Asian (7.1 %), Mixed (1.6 %), and other (1.2 %).

Following participation, all participants were invited to take part in a second study which aimed to assess the test re-test reliability of the measure. This study was advertised via Prolific 14 days after the initial study, in keeping with literature recommendations (Little et al., 2011; Marx et al., 2003). A total of 658 individuals took part, 653 of which had complete data at both timepoints. This subset of participants had a mean age of 47.3 (SD = 15.2), 49 % identified as male, 50 % as female, and 1 % as another gender identity.

4.3. Cohort 5

Although the Prolific sample was representative for age, sex, and ethnicity, other biases will exist in any recruitment method; for example, 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 certain screen-based visual sensitivities (e.g., aversion to scrolling or to high- contrast text or pattern). Therefore, we sought a final large sample recruited in an entirely different way (with different self-selection biases). We used a community health list in Wales (HealthWise Wales; HWW), where participants are not compensated for their time (the advertised incentive is to improve health research in Wales), have an older demographic than students or Prolific users (e.g., Douglas et al., 2023; Hurt et al., 2019), and lower average digital literacy is required (the survey link is directly emailed).

Volunteers in the community health list were emailed with an advert and link to participate in the 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 limit 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"*.

We received 2500 responses. Exclusion criteria were: completing less than half the survey (398), failing a comprehension check (67) or an attention check (101), implausible clinical diagnoses (12 participants reported 'yes' for every one of 20 listed conditions), or incomplete responses for the 42 items (105). The final sample for analysis consisted of 1817 participants. Mean age was 63 (SD = 13, range 18–97), 40 % identified as male, 59 % as female, and 0.6 % as another gender identity. Thirty individuals did not indicate their gender, and 62 participants did not provide their age. Informed consent was obtained from all participants, and experiments were carried out in accordance with the World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects.

4.4. Measures and Procedure

Qualtrics survey was used to deliver all measures, which included the 42 visual hypersensitivity questions, age, self-reported gender, and the additional measures listed below to assess convergent and divergent validity. Cardiff University's School of Psychology ethics committee provided ethical approval for all procedures.

Our 42 visual hypersensitivity items were prefaced by an explanation of visual discomfort, defined as "Physical pain, tiredness or strain in or around your eyes or head". We explicitly differentiated this from alternative interpretations of uncomfortable as disgusting, upsetting, or frightening. An initial question tested comprehension of the definition (see Appendix).

4.5. Adolescent/Adult Sensory Profile-visual (AASP-V; 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). 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)"*.

4.6. Sensory Sensitivity Scales-Visual (SeSS-V; Aykan et al., 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. The SeSS, similar to our approach, 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 et al., 2020).

4.7. Migraine Screening Questionnaire (MSQ; Láinez et al., 2005)

Migraine is expected to correlate with visual sensitivity. The MSQ includes five items about migraine episodes experienced. 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 MSQ shows adequate validity and reliability (Cronbach's α = 0.82; Láinez et al., 2005).

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

Symptoms of visually-induced dizziness are present across the healthy population and expected to correlate with visual hyper-sensitivity (Powell et al., 2020a; Powell et al., 2021). The VVAS is a self-report measure of visually-induced dizziness in which participants indicate the degree of dizziness they experience in nine different situations. The measure also shows good reliability (Cronbach's α = 0.94; Dannenbaum et al., 2011).

4.9. 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).

4.10. Discomfort images

To assess the relationship between the factors and visual images with properties known to induce discomfort in previous research (Penacchio et al., 2021; Wilkins, 1995), three images were shown to participants (See *Supplementary Material C*). Following Price, Powell, and Sumner, 2025, we used a novel rating scale shown to improve correlation with visual sensitivity questionnaires. The first question asked, *"Which of these statements best describes how you feel about this image?"* with five response options 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, with response options spanning "I immediately have to look away from this image" to "I could look at it for 5 min or more". Scores in response to each question were averaged across the three images.

4.11. Statistical analyses

Exploratory analyses were performed on Cohort 4 and one randomly selected half of Cohort 5. The remaining half of Cohort 5 was reserved for confirmatory analysis.

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, 2024) was used for bifactor analyses. KMO measure of sampling adequacy and Bartlett's test of sphericity both supported the use of factor analysis in these samples.

Alternative model solutions were compared, namely: a 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). Items were retained if their loading was equal to or greater than 0.30 (Costello & Osborne, 2005), and cross loadings were absent or had a difference of greater than 0.15 between factors (Worthington & Whittaker, 2006).

Of those retained, items were subsequently removed based on fit indices and conceptual replication to create a 20-item measure with 5 items per factor (CHYPS). For the subscales of this final measure, 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 & Bernstein, 1994).

Test-retest reliability for these subscales was determined using intraclass correlation coefficients (ICC). In keeping with literature recommendations (Koo & Li, 2016; Qin et al., 2019), a two-way mixed effects model using absolute agreement was used to calculate ICC for CHYPS 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).

A confirmatory bifactor model was tested using the 20 items selected for CHYPS and the remaining half of Cohort 5. The model included a general visual sensitivity factor, and a further four specific factors prespecified based on the results of the exploratory bifactor analyses. Given data was ordinal in nature, 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) > 0.95, Root Mean Square Error of Approximation (RMSEA) < 0.06, and Standardized Root Mean Square Residuals (SRMR) < 0.08 (Hu & Bentler, 1999). However, adjustments to traditional fit indices are increasingly recommended in the literature for confirmatory models. For example, χ^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/$\overline{R2}$ (where < 0.05 indicates good model fit), as recommended by Shi et al. (2018) has recently been found to be beneficial in identifying mis-specified bifactor models (Ximénez et al., 2022), particularly in the context of limiting cross loadings as is the case in the lavaan confirmatory factor model.

For completeness, both classical (CFI, RMSEA, SRMR) and adjusted (χ^2/df, SRMR/$\overline{R2}$) fit indices will be reported and were used to evaluate the model. However, as bifactor models risk overfitting (Bonifay et al., 2017; 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.

Finally, Cohorts 4 and 5 were combined to investigate convergent validity of the CHYPS using Bivariate Pearson's correlations. In these analyses, 2039 participants had complete data for the AASP-V, SeSS-V, MSQ, VVAS, and HADS-A. This was reduced to 1994 for the discomfort image variables (participants were given the option to not view the images). Evidence for convergent validity (r > 0.50) was expected between the subscales and total measure scores and the AASP-V, SeSS-V, VVAS, and discomfort image ratings. Correlations (r > 0.3) are also

Table 2
The four factors of visual hypersensitivity in Cohorts 4 (Prolific, n = 774) and 5 (HealthWise Wales, HWW, n = 1817). Items loading below 0.3 or cross-loading have been removed. (H) indicates that the item asked whether the stimuli triggered a headache. *Note. IVE = Intense Visual Environments.* Table shows strength of factor loadings across items of the second version of the questionnaire. Item loadings group together according to four factors (as seen previously). They also all load onto a general factor in the far right hand column.

Item	Brightness Prolific	Brightness HWW	Pattern Prolific	Pattern HWW	Strobing Prolific	Strobing HWW	IVE Prolific	IVE HWW	g Prolific	g HWW
Wearing sunglasses or a hat on a bright day		0.38							0.29	0.33
Getting a headache on a bright day (H)		0.39							0.50	0.59
Sunlight flickering through trees	0.38								0.52	0.64
Using a shade when driving	0.42	0.51							0.5	0.56
Dim or turn off ceiling lights	0.36	0.33							0.57	0.61
Sunlight reflecting off surfaces	0.44	0.4							0.55	0.64
Bright lights in the dark	0.34	0.32							0.59	0.65
Sudden changes from dark to light	0.41	0.34							0.52	0.60
Repeating or stripey patterns			0.43	0.43					0.61	0.72
Distortions in repeating or stripey patterns			0.39	0.36					0.61	0.68
Complex patterns (e.g., wallpaper, carpet)				0.42					0.64	0.74
Buildings or rooms with complex features			0.39	0.41					0.60	0.71
Patterned clothing (e.g., checks, stripes)			0.43	0.48					0.59	0.69
Flickering lights						0.38			0.60	0.68
TV or film with fast motion					0.47	0.4			0.53	0.69
Rotating motion						0.3			0.59	0.71
Strobing lights on TV or film					0.51	0.46			0.58	0.68
Flickering screens					0.3	0.39			0.65	0.74
Motion in video games					0.31	0.31			0.56	0.69
Strobing in venues (e.g., theatres, clubs)					0.45	0.39			0.54	0.63
Supermarkets (H)							0.41	0.44	0.52	0.58
Moving objects (H)							0.37	0.38	0.58	0.67
High motion environments							0.4		0.60	0.72
Bright colours (H)							0.42	0.47	0.58	0.65
Cluttered environments							0.45	0.37	0.57	0.61
People moving quickly							0.42	0.35	0.49	0.62
Cluttered environments (H)							0.51	0.52	0.48	0.57
Crowds moving							0.47	0.44	0.51	0.63
Supermarkets							0.45	0.48	0.48	0.58

expected with MSQ and HADS-A. The data necessary to reproduce the findings reported in this manuscript are available at https://osf.io/6489s/.

5. Results

5.1. Factor structure

In both Cohorts 4 and 5, optimal fit was identified as the bifactor with four specific factors (Table 2), consistent with the factors found in Cohorts 1–3. These are again interpreted as: Brightness, Pattern, Strobing, and Intense Visual Environments (IVE). Alternative models showed comparatively poor model fit (defined by BIC and RMSEA), or poor factor loadings that were difficult to interpret. There were some minor differences in the exact items that survived removal for threshold loading (0.3) or cross loading, but the surviving items were consistent with the same conceptual interpretation. The four factors also had consistent loading on the general factor (right hand columns in Table 2).

5.2. Cardiff Hypersensitivity Scale (CHYPS)

To create a concise scale, we selected five items for each factor to constitute a 20-item scale with four subscales. For the Brightness and Strobing subscales, we selected the five items in Table 2 that loaded (above 0.3) in both cohorts. For the Pattern subscale there were only five surviving items in Table 2 to select. For IVE, of the 8 items loading for both cohorts, we removed the lowest loading item (*Moving objects (H)*) and the items asking about headache that replicated the same trigger as other questions, since headache is a less general response (*Supermarkets (H), Cluttered environments (H)*). This left five items (*Bright colours (H), Cluttered environments, People moving quickly, Crowds moving, Supermarkets*). All selected items also had consistent loading on the general factor between 0.48 and 0.75.

The final model is displayed in Fig. 1. Each factor consisted of 5 items. The general factor was well defined; all loadings were > 0.45 and ECV values were 0.64 (Prolific) and 0.71 (HWW), supporting the presence of multidimensionality (Reise, Bonifay, & Haviland, 2013; O'Connor, 2014). Both cohort's fit indices were within acceptable range (Prolific RMSEA = 0.05 [90 % CI 0.05—0.06], BIC = −403), (HWW RMSEA = 0.04 [90 % CI 0.04–0.05], BIC = −471).

5.3. Confirmatory bifactor model

We used the remaining half of Cohort 5 in a confirmatory bifactor specified using the 20 items selected above. This model showed good fit statistics, Robust CFI = 0.95, Robust TLI = 0.93, SRMR = 0.03, aside from chi square (χ^2 (150) = 182, $p < 0.001$), and borderline Robust RMSEA = 0.09 [90 % CI 0.09 – 0.08]. Adjusted fit indices were also acceptable, $\chi^2/df = 1.21$, $SRMR/\overline{R2} = 0.04$. The complete confirmatory bifactor model, including item loadings, can be found in *Sup. Table S9*.

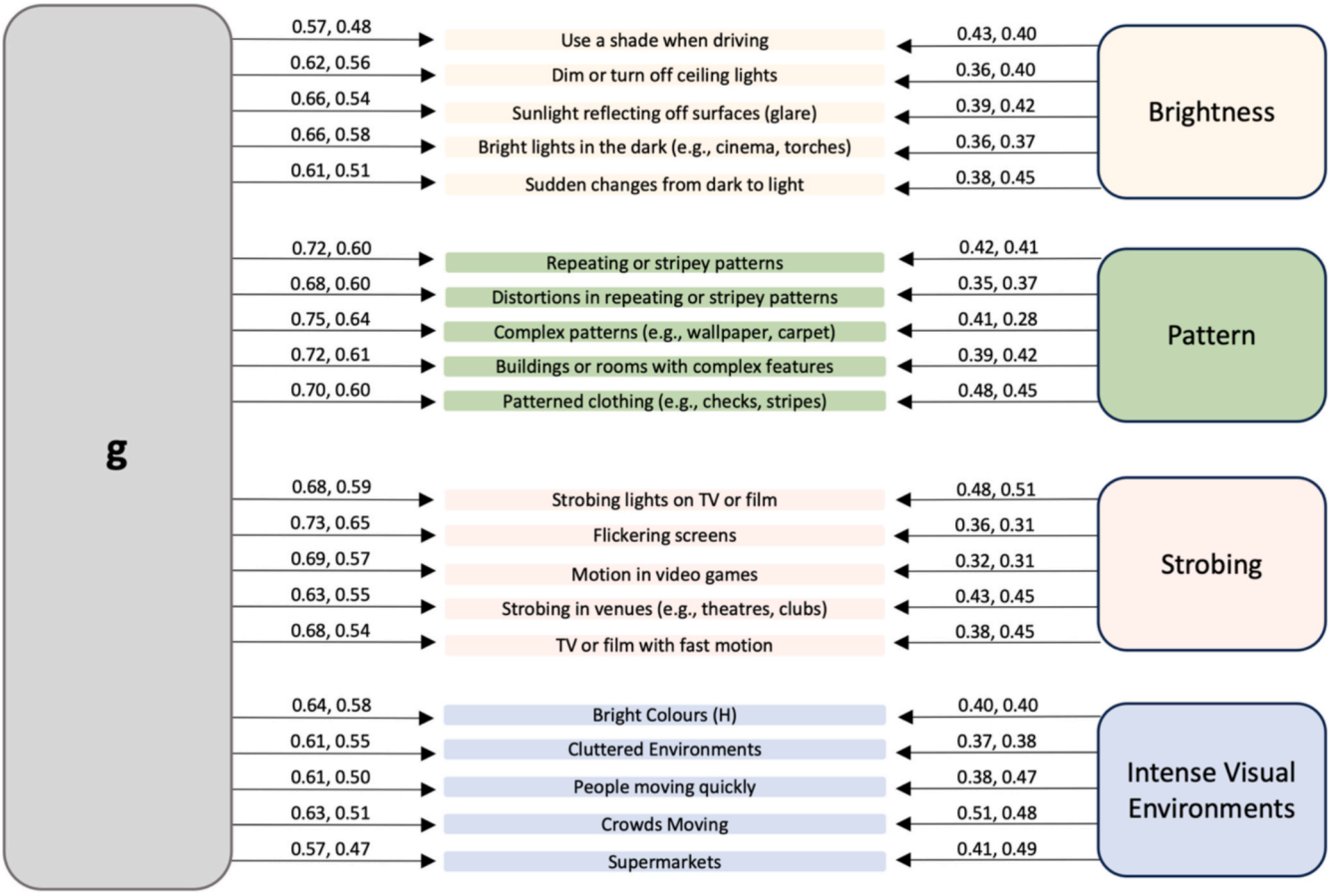

Fig. 1. The twenty items of the Cardiff Hypersensitivity Scale (CHYPS) showing the general factor loadings (g) and loadings for the four factors, for both Prolific and HealthwiseWales cohorts (first and second numbers, respectively). The full questionnaire is available in Appendix. Figure shows the final 20 questionnaire items which load both on a general factor, and one of the four factors identified previously. All loadings are greater than 0.30.

5.4. Reliability and convergent validity

Table 4 displays descriptive statistics for total and subscale scores in the total sample (combining Prolific and HWW, n = 2591), along with Cronbach's α and Macdonald's ω. Items associated with the Brightness subscale were most endorsed, and IVE items the least. Distribution plots including quartiles for each CHYPS subscale, and the total score, are provided in Supplementary Fig. S2. Reliability, as measured by α and ω, was good in all subscales (where good = α > 0.70, Nunnally & Bernstein, 1994) and good ω > 0.70 (Ponterotto & Ruckdeschel, 2007), and excellent in the total CHYPS score. Subscale correlations were largely similar in magnitude across subscales and did not suggest factor redundancy.

In terms of test–retest reliability (conducted on Cohort 4 only, n = 653), ICC for total CHYPS scores was 0.92 (95 % CI 0.89 – 0.94), indicating good test–retest reliability. This was also the case for the Brightness (0.89 [95 % CI 0.87–0.90]), Pattern (0.84 [95 % CI 0.71–0.90]), Strobing (0.90 [95 % CI 0.89–0.92]) and IVE (0.89 [95 % CI 0.87–0.91]) subscales.

Total CHYPS scores showed strong convergent validity with existing measures of visual sensitivity, the SESS-V (r (2037) = 0.86, $p < 0.001$), the AASP-V (r (2037) = 0.69, $p < 0.001$), and VVAS (r (2037) = 0.69, p < 0.001). Total CHYPS scores also showed strong correlations with discomfort reported in response to discomfort images (r (1992) = 0.60, $p < 0.001$), and time willing to spend looking at these images (r (1992) = 0.61, $p < 0.001$).

Moderate correlations were present between total CHYPS scores and measures of migraine (r (2037) = 0.52, $p < 0.001$) and anxiety (r (2037) = 0.43, $p < 0.001$). Correlations between these measures and CHYPS subscales are provided in *Sup. Table S7*.

Table 4
Summary statistics and reliability indices for each subscale calculated based on each sample's respective factor structure, and associated Pearson's correlations between each subscale. *Note. α = Cronbach's alpha, ω = Macdonald's omega, IVE = Intense Visual Environments.* Table shows reliability of total and subscale scores (all above 0.80) and correlations between factors (ranging from 0.61 - 0.69).

Total sample (Cohorts 4 and 5, n = 2591)						
Scale	M (SD)	α	ω	Brightness	Pattern	Strobing
Total	11.98 (11.03)	0.94	0.94			
Brightness	4.58 (3.71)	0.84	0.84			
Pattern	2.46 (3.06)	0.89	0.90	0.64		
Strobing	3.75 (3.73)	0.88	0.88	0.67	0.67	
IVE	1.19 (2.29)	0.85	0.86	0.61	0.69	0.64

6. General discussion

Across five samples, the different triggers of subjective visual hypersensitivity have shown four highly replicable factors with consistent conceptual interpretation: Brightness (overhead lighting, sunlight, glare), Pattern (complex wallpapers, architecture, stripes), Strobing/Motion (flashing lights in theatres, motion on screens), and Intense Visual Environments (supermarkets, cluttered or high motion spaces). A general factor was also identified and confirmed, supporting a unified concept of visual hypersensitivity, in addition to the factors. This also means that in measuring visual hypersensitivity, both total scores and subscale scores are justified. However, the exact four factor solution was not self-evident *a priori*; for example, items containing motion did not

form a single factor, and neither did all stimuli or environments with high spatial frequencies.

6.1. Theoretical implications of the factors

Three of the four factors relate to basic features of visual information: Brightness, Pattern, and Strobing/Motion (temporal change). These factors are partially consistent with current theories of excitation/inhibition balance in visual systems (e.g., Wilkins et al., 2021). Hyperexcitability of the visual cortex has been previously suggested to underly subjective sensitivity to pattern (Wilkins, 1995), colour (O'Hare, 2017), flicker (Yoshimoto et al., 2017), and motion (Fisher et al., 2022). These types of aversive stimuli can all produce large haemodynamic responses in visual cortex (e.g., Bargary et al., 2015; Gentile & Aguirre, 2020; Huang et al., 2003; Orekhova et al., 2019). However, note that current theories tend not to be specified in terms of whether hyperexcitability relates to both signal and noise, and what kind of noise, which would lead to different predictions about the relationship between subjective hypersensitivity and objective detection or discrimination tasks (Ward, 2019).

Individual differences across these three 'feature' factors could indicate differential susceptibility across regions of visual cortex. A related hypothesis has previously been made for epilepsy, where different pattern, motion, and flashing precipitants were conceptually associated with heightened sensitivity in different regions of visual cortex (Radhakrishnan et al., 2005), although several of the triggers would be grouped under the Strobing/Motion factor we identify. Wilkins et al. (1979) also describe how pattern and television sensitivity could be associated due to raster patterns in cathode ray tube televisions rather being conceptualised as different triggers.

The Brightness factor was the most heavily endorsed and aligns with photophobia research and reported sensitivity to light more generally (Digre & Brennan, 2012; Wilkins et al., 2021). However, the factor also includes situations such as glare, highlighted in participant feedback but not always explicitly reported in previous literature. Some retinal causes of photophobia have been elucidated, such as intrinsically photosensitive retinal ganglion cell (ipRGC) and trigeminal nerve mediated release of neurotransmitters, which appear to be particularly important to some forms of photophobia (Noseda et al., 2019). However, retinal causes are not sufficient to explain brightness aversion in visually healthy individuals, and imaging work has reported 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; Bargary et al., 2015; Boulloche et al., 2010). 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).

The Pattern factor aligns with a prominent theoretical framework in which visual cortices are vulnerable to over-excite with stimuli that deviate from natural properties (Wilkins, 1995). For some people this vulnerability is thought to be enhanced (for reasons unknown) developmentally or due to brain trauma, for example (Powell et al., 2021; Ward, 2019). As would be expected, the Pattern subscale displayed the greatest correlation with discomfort image ratings (*Sup. Table S7*), in line with previous research highlighting the spatial frequency and orientation properties of these types of images (Penacchio et al., 2021). Many patterns and images known to be problematic deviate from the statistical properties found in natural environments in terms of spatial frequencies and orientations (Fernandez & Wilkins, 2008; Juricevic et al., 2010; Wilkins, 1995; Yoshimoto et al., 2017). Stripes at around 3 cpd are particularly triggering. These stimuli evoke large metabolic and electrophysiological responses in the visual cortex (Huang et al., 2003, 2011; Orekhova et al., 2019; Singh et al., 2000). Such cortical responses are sometimes reported to be larger still in those susceptible to discomfort (e.g., individuals with migraine; Huang et al., 2003). Interestingly, characteristic spatial frequency tuning in visual cortex may also be altered in pattern aversion. Whilst V1 shows maximal cortical activation in response to 3 cpd stimuli and V2 typically shows low-pass spatial frequency tuning (with maximal response to approximately 0.3 cpd; Huang et al., 2011; Singh et al., 2000), V2′s characteristic low pass tuning was reported absent in participants with migraine; instead V2 showed maximal activation in response to 3 cpd (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, for whom pattern sensitivity is common (Harle et al., 2006; Hine & White, 2022).

The Strobing/Motion factor included sensitivity to the types of flashing stimuli known to be potential triggers of photosensitive epilepsy and migraine (Fisher et al., 2022; Friedman & De Ver Dye, 2009; Shepherd, 2010), as well as motion stimuli that did not load on the IVE factor, such as screen motion in action films and video games. These all include coherent motion (panning, roll, shaking, and zoom) across multiple receptive fields. Such stimuli are known to elicit headache, discomfort, and motion sickness in some individuals (Kuze & Ukai, 2008; Ujike et al., 2008). Action films and video games also often include rapidly changing viewpoints which involve regular changes in colour, brightness, and pattern, which may elicit similar perceptual and metabolic effects as strobing or flickering lights (Harding & Harding, 1999; Honey & Valiante, 2017). 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 to these stimuli (e.g., gamma oscillations; Hermes et al., 2017; Yoshimoto et al., 2017) may therefore involve similar pathways. Discomfort in response to flickering light has also been reported to correlate with evoked responses in early visual cortex (Gentile & Aguirre, 2020).

One notable omission from our factor solutions was the experience of discomfort when reading. Previous literature (e.g., Conlon et al., 1999) has framed lines of text as a form of striped stimulus. Discomfort when reading has therefore been allied with aversion to pattern. Items relating to discomfort to text were therefore included for all five cohorts tested here, with the hypothesis that these would load with other pattern-related triggers. However, these items did not load in any of the factor solutions. At first sight, this contrasts with measures such as the Visual Discomfort Scale (VDS; Conlon et al., 1999), which assesses aversion to pattern, reading, and lights. However, the VDS may represent three factors, where many reading items load separately from the items relating to lighting and pattern (Borsting et al., 2007), suggesting a dissociation between reading and other visual sensitivities that is consistent with our results.

One possibility is that reading discomfort occurs for distinct reasons from other forms of visual stress, such as accommodative or binocular disorder which can co-occur with reading delay and distortion (Borsting et al., 2007; McIntosh & Ritchie, 2012). Indeed, Saksida et al. (2016) report children with dyslexia show similar levels of visual sensitivity to striped patterns (measured by the Pattern Glare task; Evans & Stevenson, 2008; Wilkins, 1995) as other children. It is also possible that it is the reading environment itself, rather than the text stimulus, which causes discomfort whilst reading (e.g., see Laycox et al., 2024). Our reading items did not assess this.

It is also possible that people with reading discomfort are underrepresented in questionnaire research (since it involves reading), which may in turn limit conclusions about reading triggers in our cohorts. However, the reading questions did not show floor effects or restricted variance compared to other questions (variance and skewness values for this question were within one standard deviation of the average of all other questions; see *Sup. Table S8*), so we do not believe this potential limitation fully explains why they did not load with the pattern factor.

The final factor, IVE, consisted of comparatively more complex visual inputs than those defined by the three feature factors. Specifically,

IVE comprised questions about busy, crowded, or cluttered environments, such as supermarkets, watching fast-paced sports or crowds moving. The role of complex, urban stimuli, and high contrast colour in visual sensitivity has been reported previously (Le et al., 2017; O'Hare et al., 2023). Such environments also deviate from the statistics of common natural scenes, showing more power in mid-high spatial frequencies just like discomfort images and patterns (Penacchio et al., 2021; Powell et al., 2021; Wilkins, Penacchio, & Leonards, 2018). Therefore, one possibility was that supermarket-like environments would load with pattern sensitivity, while moving crowds would load with motion and strobing. It is therefore notable that they consistently formed a separate factor in all cohorts.

The IVE factor items also bear striking consistency with the visually induced dizziness triggers in conditions such as PPPD (Popkirov et al., 2018), which include supermarket aisles and busy moving traffic. Indeed, recent work finds visually induced dizziness 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 scores also supports this association and provides evidence of convergent and construct validity for this factor (see *Sup. Table S7*).

The framework of hyperexcitable visual cortex has also been suggested for these complex environments (Le et al., 2017; Powell et al., 2021). However, this would not explain why the IVE question did not load with the basic visual features prevalent in each environment. Thus, it appears that for this factor, it is the multisensory nature that is most important, rather than the specific visual features contained in each stimulus. We may therefore predict differential cross-modal correlations (i.e. with factors of auditory or tactile hypersensitivity) in IVE compared to the 'feature' factors, which future study will seek to investigate. This broader implication of the IVE factor would then suggest mechanisms that go beyond visual systems, which may or may not be the same for everyone.

6.2. Relevance to clinical diagnoses and areas of neurodiversity

At this stage, a theoretical distinction between the IVE factor and the three 'feature' factors remains speculative. We found similar loading of all factors on the general factor, and similar cross-factor correlations. If the speculative distinction has any merit, it may predict that some neurological, psychiatric, and developmental conditions or areas of neurodiversity show more association with IVE, while others show more association with the three feature factors.

For instance, the prominent theoretical perspective for migraine (Wilkins et al., 2021), dyslexia (Hancock et al., 2017), and epilepsy (Radhakrishnan et al., 2005), is that of visual cortex hyper-excitability, with particular focus on the uncomfortable nature of brightness (photophobia), flicker, and stripes for these groups. This would predict alignment with the three 'feature' factors of visual hypersensitivity. These factors further have tempting mapping to known properties of neuronal populations in visual cortex, as well as models of excitation and inhibition in local cortical circuitry (Orekhova et al., 2019; Radhakrishnan et al., 2005). For instance, many feature-based stimuli known to be problematic (e.g., patterns, flickering or bright lights) deviate from the statistical properties found in natural environments in terms of temporal frequency or spatial frequencies and orientations (Fernandez & Wilkins, 2008; Juricevic et al., 2010; Yoshimoto et al., 2017). Relative vulnerability for these visual features might then vary across diagnoses; for example, light, flicker and motion are commonly researched in migraine and TBI (e.g., Diel et al., 2021), while for dyslexia, striped patterns have been emphasised (Evans, Cook, Richards, & Drasdo, 1994; Nandakumar & Leat, 2008).

Other theoretical approaches have informed the study of autism, anxiety, and PTSD, which instead highlight influences from outside the visual system. For instance, activation of (or connectivity with) amygdala (Schwarzlose et al., 2023; Shin & Liberzon, 2010), or the role of emotional regulation, arousal, defence mechanisms, and hypervigilance in anxiety and related disorders (Fleming et al., 2024; Kimball, 2023). In autism, multiple whole-brain theories exist, including a general difference in excitation/inhibition balance (Rubenstein & Merzenich, 2003). There is also some emphasis on overwhelm to cluttered environments (Parmar et al., 2021; Robertson & Simmons, 2018). PPPD, a neurological condition whereby dizziness is triggered or exacerbated by settings similar to those described by the IVE factors (e.g., supermarkets; Staab et al., 2017), has also been proposed to involve abnormal interactions between visual cortex and other areas, including limbic structures (Castro et al., 2022). It is therefore possible that clinical diagnoses or neurodevelopmental conditions which are associated with differences in the activation or connectivity of regions beyond the visual cortex may show comparatively enhanced sensitivity to IVE.

However, recent theory in migraine suggests a dysregulation within the limbic system – hypothalamic 'loss of control' – as a potential cause of multi-sensory sensitivities and other migraine symptoms (Stankewitz et al., 2021). This may imply a more nuanced distinction between neurological, developmental, and mental health diagnoses than can be afforded by a dissociation of our four-factor solution. Furthermore, settings described by the IVE factor (e.g., supermarkets) also contain stimuli with the individual characteristics described in the feature factors (e.g., repeating patterns, flickering lights), and would similarly deviate from natural scene statistics. Thus, IVE's potential association with wider brain activity and the theory of visual cortex hyperexcitation are not mutually exclusive.

How the four factors of visual hypersensitivity present across a wide range of clinical diagnoses or neurodivergence is investigated in Price, Sumner, and Powell (in press). Beyond this, future study could also investigate how the same triggers may cause different responses in different populations. For instance, the result of discomfort to settings represented by the IVE factor (e.g., supermarkets), may primarily lead to anxiety in one clinical population (e.g., obsessive compulsive disorder) and exacerbated fatigue in another (e.g., fibromyalgia). Similarly, there may be differential impacts across the developmental trajectory; for example, lighting sensitivity may affect learning in classroom settings for children (Negiloni et al., 2019; Winterbottom & Wilkins, 2009; Yao et al., 2024). Understanding how visual sensitivities affect specific symptom profiles could strengthen advocacy work which seeks to make sensory environments more accommodating.

6.3. Theoretical implications of the general factor

In discussing the four factors, it is important to remember that the general factor is also strong. This would be consistent with the framework of excitable visual cortex but could also be consistent with wider networks implicated in the interpretation of hyperexcitation as discomfort.

It is possible that individual differences in general 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) should be sparse based upon their statistical properties, to prevent metabolic cost (Olshausen & Field, 1996), and to prevent ceiling effects in neural coding – it is easier to discriminate change if the system is not overloaded. In contrast, stimuli that deviate from commonly encountered environments elicit a greater neural response (Juricevic, Land, Wilkins, & Webster, 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 (Ward, 2019).

It is also important to acknowledge that subjective sensitivities tend to correlate cross-modally (e.g., Price et al., 2021). Some theoretical

perspectives (and the tools that accompany them) make no distinctions between visual, auditory, and tactile sensitivity, for example. There are two possible explanations for cross-modal correlation: the mechanisms that make a visual cortex susceptible are shared across other sensory cortices, or else mechanisms beyond the modality-specific cortices are important.

Theories based on sensory cortex hyperexcitability tend to assume that high levels of neural activation in sensory cortices are intrinsically uncomfortable and therefore differences in discomfort result from differences in sensory activity. This could reflect either a homeostatic mechanism to prevent metabolic stress or retinal damage (Hibbard & O'Hare, 2015; Wilkins et al., 2021), or a feeling generated from inefficient processing (Gentile & Aguirre, 2020). Either way, the assumption is that individual differences in discomfort result from individual differences in sensory activity. However, we need not assume this. Another possibility, more aligned with literatures that emphasise influences beyond the visual system itself, could be individual differences in how high levels of sensory activity are interpreted by wider brain networks – such as the limbic system, 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 contribute to a general capacity for experiencing subjective sensitivities (see also Ward, 2019 for related discussion).

6.4. *Practical implications – Measuring hypersensitivity*

CHYPS is a 20-item questionnaire that captures the four factors and can also provide an overall score. It is statistically and conceptually coherent, with classical test theory scale reliability, convergent validity, and test–retest reliability. 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. These aspects enabled us to create and select items that are both theoretically relevant and represent individual experience. We intend to continue this work across sensory modalities, according to the same development principles.

CHYPS focusses on aversive hypersensitivity. It does not measure other aspects of sensory difference that can arise across populations, such as the concepts of hyposensitivity or sensation seeking.

7. Limitations

Our focus on functional impact, in order to help people calibrate their responses (e.g., with questions about avoiding situations), means that we have collapsed across a distinction that has been made in some literatures between perceptual experience and behavioural avoidance. For example, in Dunn's model which underlies the AASP (Brown & Dunn, 2002), subjective sensory sensitivities are represented by two subscales of 'avoidance' (behaviours which limit exposure to stimuli) and 'sensitivity' (dislike for stimuli and distractibility in its presence). In our research and previous studies, the correlation between these subscale questions is always strong (e.g., Price et al., 2021). However, in some research and cohorts, such as autistic children, it may be theoretically and practically important to distinguish the sensory experience from the behavioural responses (e.g., MacLennan et al., 2020; Tavassoli et al., 2014).

A second limitation concerns sampling techniques. The student samples were not highly varied in age, gender, ethnicity, or education (possibly with lower likelihood of reading discomfort than a general population sample, although some students do ask for lecture slides to be altered due to reading discomfort). Students are also generally experienced and quick questionnaire respondents motivated by course credit (with accompanying attention risks, though attention checks were included). The Prolific samples, although representative of UK sex, age and ethnicity distributions, will have self-selection biases in other ways, and especially may not include a representative number of individuals with high visual sensitivities to screen motion or reading (note, however, that although the scores were negatively skewed, there were still many high scoring participants). They are also experienced, and quick questionnaire respondents motivated by payment. The HealthWise Wales sample, on the other hand, were less likely to be such regular computer users and took longer responding to the questionnaires, but are not fully representative of age and gender distributions. Therefore, each cohort has biases, but these biases are not the same across all cohorts, minimising the likelihood that the results apply only to limited populations.

Limitations in the confirmatory bifactor model fit should be highlighted. Fit statistics including CFI, TLI, and 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 into consideration of the chi square statistic, 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., 2017) and both theory and parsimony should be also considered. Contextual and theoretical factors, including the replicated factor structure across many cohorts also support the current bifactor model.

One item showed non-significant loading on its hypothesized specific factor in the confirmatory model. The colour item ("*When there are lots of bright colours around me, I tend to get a headache*") loaded strongly on the general factor but weakly and non-significantly on the IVE factor in confirmatory analyses. It is possible this is due to the differing restrictions of a confirmatory bifactor model, which constrains cross-loadings. Despite this, there is justification for retaining the item in the measure. The content of this item was taken from feedback during development, it loads strongly on the general factor, and it survived item selection in the final bifactor model in Fig. 1. It will however be important for future work using the CHYPS to further establish the status of the item in other samples.

Overall, the general factor was stronger in the confirmatory model, while in turn several items showed reduced loadings on their factors. 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 in may also be influenced by the age range of the participants (mean age = 63) in relation to experience with some of the items, such as video games. There is also evidence to suggest age-related reduction in visual sensitivities (Evans & Stevenson, 2008; Kelman, 2006; Qi et al., 2019), which could change the balance between general and specific factors.

7.1. *Summary*

We aimed to discover the factor structure of aversive visual hypersensitivity, and develop a tool to measure it. We assessed a wide range of triggers derived from previous research and new qualitative responses, across 5 cohorts including over 3500 participants using three different recruitment strategies. We consistently found four factors that were statistically and conceptually coherent: Brightness, Pattern, Strobing, and Intense Visual Environments. There was also a strong general factor

unifying the overarching concept of visual hypersensitivity. We selected 5 items per factor to produce a new questionnaire, CHYPS, which shows good psychometric properties, including construct, convergent, and test–retest reliability.

CRediT authorship contribution statement

Alice Price: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Petroc Sumner:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Georgina Powell:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2025.108610.

Data availability

The data necessary to reproduce the findings reported in this manuscript are available at https://osf.io/6489s/.

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