Synaesthesia as a Model for Assessing Individual Differences in Visual Perception and Memory Performance

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Author Note

The study data and materials will be shared openly as part of the publication of the article. The proposed protocol has been reviewed and accepted by the ethics committee of the University of Sussex (ref. ER/JAMIEW/30). The study has received financial support from the Swiss National Science Foundation (ref. 204314). The authors have no competing financial interests to declare.

Abstract

In this study, the cognitive profile of synaesthesia (a perceptual condition in which primary experiences, such as perceiving digits or words, elicit extra secondary sensations) is used as a model system to assess visual perceptual abilities and memory performance in the general population. Synaesthesia serves as a suitable framework for examining variations in visual perception and visual memory among individuals, as it has been associated with visual perception and memory advantages. We compare the cognitive profile of three groups: synaesthetes, non-synaesthetic relatives of synaesthetes, and non-synaesthetic non-relative controls. We use measures of visual perception and performance on short and long-term memory tasks with colour and location manipulations to derive a detailed and multivariate profile of each group. A key strength of our approach is that perception and memory tasks are perfectly matched in terms of generating the same dependent variable. We also assess mental imagery, cognitive style, and motivation using questionnaires. We expect our work to further develop theories on the relationship between perceptual ability and memory performance and to elucidate whether synaesthesia is epiphenomenal or functionally related to different or enhanced cognitive processes.

Keywords: Perception, memory, synaesthesia, relatives

1. Introduction

Individual differences research in cognitive psychology seeks to understand how people use cognitive mechanisms in different ways to perform the same task. It aims to explain why some participants systematically differ from the aggregate data pattern, for reasons other than statistical noise (Logie, 2018). Recent attempts to develop predictive models of brain-behaviour relationships have shown that, whilst successful for most people, there are subgroups within the general population who are consistently hard to fit (Greene et al., 2022). One group that tends to deviate from the norm in terms of their cognitive profile is people with synaesthesia. Synaesthesia is a perceptual condition in which primary experiences, such as perceiving digits or words, elicit extra secondary sensations (Simner, 2012; Simner & Hubbard, 2013; Ward, 2013; Ward & Simner, 2020). Synaesthesia is an appropriate model system to test individual differences in visual perception and visual memory because these individuals are a largely hidden subgroup within the neurotypical population (it is not a disorder) with known differences in cognition, for example displaying enhanced visual acuity (e.g., Banissy et al., 2009, 2013; Barnett et al., 2008) and memory abilities (e.g., Lunke & Meier, 2018; Ovalle-Fresa, Ankner, et al., 2021; Rothen et al., 2012; Rothen & Meier, 2010). Here we take this an important step further by determining the extent to which individual differences relating to perception and memory are related (i.e., such that variation in one explains variation in the other). We utilise people with and without synaesthesia as a 'natural experiment' of cognitive variation to determine the extent to which individual differences in perception and memory co-occur within the same visual characteristics, also noting that synaesthetes have a heterogeneous presentation (e.g., varying in whether synaesthetic experiences involve colour or spatial experiences or not). This allows us to examine differences amongst synaesthetes as a secondary question.

Historically, perception and memory are considered largely separable domains of cognition (e.g., Marr & Brindley, 1997; Ranganath & Ritchey, 2012). However, tests of perception and memory are typically not matched in terms of either stimulus properties or task

demands. When they are more closely matched, similarities between perception and memory can be found in terms of both neural substrates and behaviour (e.g., Graham et al., 2010; Rothen et al., 2012). Research including individuals with other specific conditions affecting perception, memory, and mental imagery, also suggests a closer link between these cognitive processes than previously thought. In cases of amnesia difficulties in both perception and memory are apparent when using similar stimuli, such as scenes (Barense et al., 2012; Lee et al., 2005). People with aphantasia (who lack visual mental imagery) show slower response times to equivalent tasks both when perceiving and imagining from memory (Liu & Bartolomeo, 2023).

Here, to further probe the link between perception and memory, we use a delayed estimation (continuous report) paradigm that can be adapted as a fair test across putatively different cognitive domains (perception, short-term, and long-term memory) and visual characteristics (colour, location) (see Brady et al., 2013; Fan et al., 2016; Ovalle-Fresa, Ankner, et al., 2021; Schurgin, 2018 for similar paradigms). To measure how perception and memory performance may vary according to individual differences in the vividness of visual mental imagery and cognitive style, we use questionnaires to capture differences between select healthy special populations: synaesthetes, their non-synaesthetic relatives and controls. In doing so, we can contribute evidence to debates regarding the modularity and structure of cognitive systems in the brain (including differences in the processing of spatial and colour object features) and can also examine the extent and magnitude to which differences in perception and memory exist in the general population, rather than in extreme cases like amnesia.

Synaesthesia consists of two fundamental elements: the presence of a stimuli that triggers the synaesthetic experience (the "inducer") and the synaesthetic experience itself (the "concurrent") (Grossenbacher & Lovelace, 2001). Here we focus on two of the most common types, namely grapheme-colour synaesthesia (where language units such as graphemes or words trigger colour sensations) and sequence-space synaesthesia (where numbers or other

ordered sequences are experienced as if they were points in space) (Ward & Simner, 2022). In terms of cognitive differences, it is generally observed that people with synaesthesia display enhanced visual perceptual sensitivity for colour information, report richer mental imagery, and an enhanced memory performance as compared to controls (Banissy et al., 2013; Barnett & Newell, 2008; Lunke & Meier, 2018; Rothen & Meier, 2010). Some studies show that memory advantages are specific to grapheme-colour synaesthesia and absent from sequence-space synaesthesia (Lunke & Meier, 2020), while others do not show a difference between synaesthesia types (Rothen et al., 2012). As such, it remains debatable whether the cognitive differences linked to synaesthesia occur irrespective of how it is manifested, in terms of inducer-concurrent pairings, or not (noting that these are not mutually exclusive options). These are also linked to different theoretical accounts.

There are two main theoretical accounts of cognitive differences in synaesthesia which predict a link between the nature of the memoranda and the profile of enhanced memory in synaesthesia: the “dual-coding” and “enhanced processing” accounts. In the dual-coding account of synaesthesia, the synaesthetic experience is understood to enhance memory performance by making available to synaesthetes additional retrieval cues in memory representations (Ghirardelli et al., 2010; Smilek et al., 2005). Specifically, performance advantages are perceived to manifest for verbal material due to additional encoding as a mental image (Paivio et al., 1969). However, not all results fit with this account. For example, while Radvansky et al. (2011) found superior letter-spans but not number-spans in a group of letter-colour synaesthetes (evidence for dual-coding), other results directly testing the dual-coding account have not found a verbal advantage for synaesthetes with coloured letters but not numbers. Superior performers included synaesthetes with coloured numbers only (Smees et al., 2019). Some evidence also suggests that synaesthetes tend to have better visual memory (e.g., for colour and abstract fractal patterns) than verbal memory (Ward et al., 2013) and that grapheme-colour synaesthetes tend to think more visually and seem to rely less on semantic connotations (Radvansky et al., 2011). This suggests that advantages go beyond

improved memory from dual-coding alone and indicates that some element of memory is atypically sensitive in this group, rather than the synaesthetic experiences manifesting from a typically functioning memory system.

In the 'enhanced processing' account of synaesthesia, a central premise is that there are fundamental differences in the efficiency of some component of the memory system in synaesthetes that are not directly linked to synaesthetic experiences (Banissy et al., 2009; Baron-Cohen et al., 1993, 1996; Lunke & Meier, 2020; Rothen et al., 2012). For example, having enhanced memory for colour in general (e.g., remembering the colour of someone's clothes) rather than having colour as an extra experience (e.g., remembering someone's name by its synaesthetic colour). Here, wider changes in the visual system of synaesthetes are understood to give rise to a memory advantage, in addition to enhancements in certain perceptual abilities. The idea that individual differences in perception and memory are causally associated (for the same kind of memoranda) sits within a broader literature postulating a view of brain organisation in which regions are optimised for processing certain kinds of information (e.g., object versus location) but shared across all kinds of cognitive processes such as perception imagery, short- and long-term memory (e.g., Graham et al., 2010). This representational view of memory and perception does not rely on distinctions between different memory systems but emphasises the characteristics of the represented information, from simple features (e.g., colour) in early visual areas to feature conjunctions (e.g., individual objects) to conjunctions of feature conjunctions (i.e., complex visual scenes) in the hippocampus, at the endpoint of the visual ventral stream. Evidence for this account comes from studies on animals and brain-damaged patients (Cowell et al., 2010, 2019; Graham et al., 2010; Saksida, 2009), as well as neuroimaging and psychophysics results (Gardette et al., 2022; Kent et al., 2016). Evidence from grapheme-colour synaesthesia suggests enhanced functioning of the visual ventral stream in terms of greater EEG visual-evoked potentials to stimuli that preferentially engage it (e.g., Barnett et al., 2008), psychophysical evidence of enhanced colour and shape perception (Rothen et al., 2018), and

better visual memory for shape and colour (Lunke & Meier, 2018; Pritchard et al., 2013; Terhune et al., 2013).

The extent to which different types of synaesthesia are linked to different profiles of enhanced processing is unclear. In grapheme-colour synaesthesia, several studies have shown that enhanced memory does not reliably extend to remembering the location of objects (Rothen & Meier, 2010; Yaro & Ward, 2018; Pritchard et al., 2013), a cognitive ability that might be expected to lie with the dorsal 'where' stream (e.g., Mishkin et al., 1983). A largely untested hypothesis is that synaesthetes with spatial concurrents (i.e., sequence-space synaesthesia) may show the complementary profile to grapheme-colour synaesthetes of enhanced processing of location rather than colour. That is, the manifestation of synaesthesia may be tied to relative enhancements of the visual ventral stream (favouring object and colour perception and memory in grapheme-colour synaesthesia) or visual dorsal stream (favouring location perception and memory in sequence-space synaesthesia). An alternative view is that there is an overarching cognitive profile linked to synaesthesia that is independent of its particular types but may, instead, be linked to synaesthesia per se. Certain questionnaires of cognitive style (e.g., attention-to-detail; Van Leeuwen et al., 2020; Van Leeuwen et al., 2021) and some multivariate test batteries (Ward & Filiz, 2020) extend to heterogeneous manifestations of synaesthesia (including the number of types that a person has). Of course, specific versus general cognitive differences need not be mutually exclusive: some individual differences in cognition may be linked to synaesthesia per se, and others to the specific type of synaesthesia.

These different accounts also make different predictions about the extent to which individual differences in cognition related to synaesthesia constitute an endophenotype; that is, first-degree relatives of synaesthetes may share these individual differences despite lacking synaesthesia. In the dual-coding account the prediction is that non-synaesthetic relatives would not show the same pattern because they lack synaesthesia and so cannot use it to their advantage. For the enhanced processing account, the predicted pattern would

depend on whether enhanced processing acted as a cognitive disposition towards synaesthesia (in which case, one could have the disposition without developing synaesthesia) and whether that disposition was specific (to one type of synaesthesia) or general in nature. There is a genetic component to synaesthesia (Bargary & Mitchell, 2008; Fisher et al., 2019) and there is some evidence that it is generic in nature insofar as synaesthetic families contain members with different types (as opposed to some families having only grapheme-colour and others having only sequence-space). It is possible to have monozygotic twins where only one twin has synaesthesia (Bosley & Eagleman, 2015; Van Leeuwen et al., 2021; Smilek et al., 2005). However, the non-synaesthetic twin may still have individual differences that resemble that of a synaesthete. Using a machine learning classifier to discriminate synaesthetes from (unrelated) non-synaesthetes, based on their cognitive profile, it was found that related non-synaesthetes had an intermediate profile (Ward & Filiz, 2020). This is not a trivial finding of showing that genetically related people are cognitively similar but, instead, pairs of individuals from different families (and often on different continents) can be shown to be cognitively similar by virtue of having a first-degree relative with synaesthesia. Similarly, autism is found to co-occur not only within individuals with synaesthesia but amongst first-degree relatives who lack synaesthesia (Nugent & Ward, 2022).

The present study uses methods influenced by the earlier research of Ovalle-Fresa et al. (2021), contrasting perception and memory with the same paradigm, and Ward and Filiz (2020) which examined the cognitive profile of non-synaesthetic relatives of synaesthetes. In Ovalle-Fresa et al. (2021) visual perceptual abilities and the accuracy of memory for colour was assessed across a visual perception task, a short-term memory task with load manipulations (either one, three or five images presented in various colours at once) and a long-term memory task where participants were asked to memorise object-colour associations. Results showed that grapheme-colour synaesthetes and colour experts share a common profile of enhanced visual perceptual ability and short-term memory in contrast to non-synaesthetic individuals from the more general population (there were no group

differences in long-term memory and overall performance on that task was close to chance). A key strength of this approach is that perception and memory tasks are well matched in terms of generating the same dependent variable and being largely equivalent in terms of overall cognitive demands (aside from the ones of interest, such as passage of time). We measure the precision of perception and memory as a continuous variable rather than binary decisions (which necessarily entail some decision criteria). This study significantly expands the earlier study of Ovalle-Fresa et al. (2021) by comparing two different kinds of visual characteristics (colour, spatial location), including different kinds of synaesthesia, and considers whether these kinds of differences constitute an endophenotype present in the relatives of synaesthetes or are more directly related to the presence of synaesthesia per se. The long-term memory task has been changed to be easier by comprising several learning attempts over smaller blocks. We aim to determine the extent to which individual differences in memory and perception co-occur and, if so, whether they are material-specific, whether they depend on the specific manifestation of synaesthesia (involving colour or not) or depend on other individual differences that happen to be more common in synaesthesia (as an endophenotype).

1.1. Hypotheses

The hypotheses, sample rationale, analyses, and possible outcome interpretations are summarised in Supplementary Table 1. The hypotheses are stated as follows:

[Hypothesis 1]. Synaesthetes will display enhanced visual perception and memory advantages relative to non-synaesthetes. Specifically, this should manifest itself as more precision in the choice of colours and locations across the tasks (perception, short-term memory, long-term memory).

[Hypothesis 2a]. Individual differences in performance on the perceptual task will predict performance on the memory tasks. Specifically, significant correlations should be observed

between the precision of perception (of colour and location) and the corresponding visual characteristics when presented in equivalent short-term memory and long-term memory tasks.

[Hypothesis 2b, contingent on Hypotheses 2a]. The significant positive relationship between perception and memory will remain when synaesthesia status and other potential confounds (e.g., age, motivation, imagery) are included in a regression model.

[Hypothesis 3]. Grapheme-colour synaesthetes will have better memory and visual perceptual abilities for colour and sequence-space synaesthetes will have better memory and visual perceptual abilities for location, in comparison to each other and non-synaesthetic controls. Individuals with both types of synaesthesia will show advantages in both tasks.

[Hypothesis 4]. Relatives of synaesthetes will exhibit a similar pattern of visual perceptual ability and memory performance as the synaesthetes, albeit intermediate in magnitude. They will outperform non-synaesthetes who are not first-degree relatives of a synaesthete in the perception and memory tasks.

2. Methods and Materials

2.1. Participants

Three groups will be recruited: (1) participants with at least one type of synaesthesia (grapheme-colour and/or sequence-space) (2) first-degree non-synaesthetic relatives of synaesthetes and (3) non-synaesthetic non-related controls. Synaesthetes will be recruited by means of our databases of synaesthetes who are willing to volunteer in experiments, synaesthesia groups on social media, word-of-mouth, and participant-pools at the UniDistance Suisse and the University of Sussex. Synaesthetes will have passed the relevant tests of consistency, where high test-retest consistency is indicative of being a synaesthete. A mean score of < 135 in CIELUV colour space using the method of Rothen et al. (2013) is indicative of grapheme-colour synaesthesia. Where possible, within the grapheme-colour synaesthesia group, we will prioritise recruitment of participants who report colours for most letters and digits as this ensures a more robust assessment of synaesthesia. For sequence-space

synaesthesia, we will use the method of Ward et al. (2018) and a cut-off score of < -2 SD of randomly permuted consistency scores (Ward, 2022) plus a questionnaire score of < 19. First-degree relatives will be recruited via their synaesthetic relative. Controls will be recruited through internet-based participants databases, such as Prolific.

2.1.1. Sample Size Determination

The study of Ovalle-Fresa et al. (2021) is the most similar to the current study in that it used the same paradigm albeit using colour only (not location). Ovalle-Fresa et al. (2021) reported group differences (synaesthetes versus non-synaesthetes) in visual perception of *d* = 1.07, and for the short-term memory task loads of one, three and five, had effect sizes of *d* = .83, .64 and .37 respectively (mean *d* for short-term memory of 0.61). As our hypothesis predicts a main effect of group for short-term memory we do not require significance at each and every load level and use the mean effect size for power calculations. Using G*Power (Faul et al., 2007) with a significance level (alpha) of 0.02 and power = 0.9, revealed that a minimum sample size of 61 per group would be required for a *d* of 0.61 (and be well powered for d = 1.07). We propose an N of 100 for each of the synaesthete and control groups to allow for these effect sizes being overestimates and to allow for greater heterogeneity within the synaesthetes compared to earlier research which only used grapheme-colour synaesthetes. Recruiting non-synaesthetic relatives is likely to be more challenging and we set our limit at N=61, accounting for attrition across testing sessions. To meet the target of N=61 relatives, we may continue recruitment of relatives after the N=100 target of synaesthetes is met (e.g., we may have to test 130 families to find 100 synaesthetes and 61 willing non-synaesthetic relatives).

Ovalle-Fresa et al. (2021) did not find a group difference in long-term memory but their task was very difficult with many participants performing at or near chance. Their version used a single learning block with a single large set of 40 associations. The task has been modified in the current study so that associations to 45 objects are learned over several smaller blocks (3 blocks of n = 15 objects) and with the addition of feedback after each trial (cf. also Ovalle-

Fresa, Uslu, et al., 2021). The meta-analysis of Ward et al. (2019) reported a mean long-term memory effect size of *d* = 0.61, so the study is considered sufficiently powered to detect this. For our correlation analysis, taking a combined sample size (three groups) of N = 261 would be sufficient to detect a correlation coefficient of .13 with a power of 0.9 (alpha = .02).

We note that the above power calculation is based on power for comparison of two independent means. This is because no prior research as to the effect sizes for comparison between synaesthetes and their relatives exists. However, if the difference between synaesthetes and their relatives is of a similar magnitude to the difference between synaesthetes and non-synaesthete controls then we do have sufficient power to detect this (at power = 0.9, alpha = 0.02), but power is lost at smaller effect sizes. We also conduct multivariate analyses such that multiple smaller univariate effects between groups may yield more robust differences.

2.1.2. Exclusion and Inclusion Criteria

All participants will be aged between 18-55 years old (the upper age is based on Brockmole & Logie, 2013) and will have normal or corrected-to-normal vision, as well as sufficient English to understand the task instructions and questionnaires. To determine eligibility and group membership, prospective participants will be asked to complete a brief online screening questionnaire. Here, as well as asking their gender, age and education for matching purposes, participants will complete online versions of the Farnsworth Dichotomous Test (D15) and Ishihara Test for colour blindness (e.g., https://www.color-blindness.com). We will apply public norms for determining exclusion based on colour blindness test results.

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Participants will also be provided with a brief description and pictorial representation of what synaesthesia is and will be asked to indicate using response-boxes whether they think that they have synaesthesia, with the options “I am sure I do not have it”, “unsure” and “I am sure I do have it” (Ward & Filiz, 2020). All relatives and controls, irrespective of their response-box selection, will be subsequently provided with online consistency tests (see *Materials* for

more detail about the consistency tests used for this purpose). Should they pass the consistency test, they will be allocated to the synaesthesia group but otherwise will be included in the respective relative or control group. Those who fail to take the test will be excluded. As synaesthetes recruited through our database have previously completed these tests, they are not required to repeat these online consistency tests. We note previous research demonstrating that the consistency scores of participants improves if they take repeated tests (Ovalle Fresa & Rothen, 2019). While this study did not explicitly include a synaesthete group, it is feasible to assume that these improvements at re-test may also apply to synaesthetes. Note also that we do not use individual differences in the level of consistency in any analysis nor as a proxy for synaesthetic strength (see Lacey et al., 2021), but simply as a way of confirming synaesthetic status. Although minor changes in colour associations or strength have been noted (across time), the presence of synaesthesia per se is considered an enduring trait in adulthood (Meier et al., 2014). We will exclude any session that is completed in an unrealistically fast timeframe (less than 30 minutes). Partial datasets where participants terminate a session early will also have that session excluded. Complete sessions will be included if they are relevant to one or more hypotheses (e.g., a correlation between perception and long-term memory does not require a complete short-term memory dataset).

The dependent variables consist of accuracy (measured in degrees) for colour and location (see *Analysis plan* for more detail). As we expect mean accuracy to differ between groups, outliers will be determined separately for each task, condition (colour or location) and group (synaesthetes, relatives and controls). Samples that are > 2.5 standard deviations from each group mean will be excluded for the visual perception task, visual short-term memory task (removed relative to the group mean in each load condition), and the final learning block of the long-term memory task (the latter ensures participants learn to a broadly similar level but is more tolerant of differences in the learning rate).

2.2. Materials

All materials and R scripts used in the experiment will be made available on Open Science Framework (OSF) (see https://osf.io/pjb6e/?view_only=d467ebf4c1f94076ae4ac61298255065). The contents will be updated (it currently contains pilot materials) and the read-only link will be changed to a permanent link upon acceptance for publication of this manuscript.

2.2.1. Consistency tests

Online versions of consistency tests will be provided to relatives and controls, as well as any synaesthetes who are recruited outside of the Sussex Database (e.g., participants from synaesthesia groups on social media). We utilise a stopping rule for these tests such that, if after presenting all stimuli once, more than 90% of stimuli have not been associated with a colour or spatial location, participants are advised that they "do not appear to associate stimuli with colours/spatial locations" and are given the option to click through to the main experiment or to continue for two further repetitions of the consistency test. As all synaesthetes in the Sussex database have previously completed these tests, we do not ask them to repeat them and instead ask for their recruitment ID number so that we can verify which type(s) of synaesthesia they have.

Grapheme-colour synaesthesia status will be confirmed using a consistency test which includes questions related to potential synaesthetic experiences (cf. Ovalle Fresa & Rothen, 2019; Rothen et al., 2013). In total we present 36 stimuli (ten digits and 26 letters). Stimuli consist of some of the following potential synesthetic inducers (depending on what is reported as present): the letters of the alphabet (A-Z), digits (0-9), days of the week (Monday-Sunday), months of the year (January-December). The stimuli are presented alongside a continuous colour palette (resembling a disk) as well as a vertical scale on the right side, which transitions from white to black. The colour palette includes a circle that respondents can adjust using the computer mouse to select colours. The vertical scale adjusts the luminance of the colours

within the palette. The colour palette and luminance bar collectively represent the entire spectrum of colours that a computer screen can display. Below the colour palette, there are two buttons: one on the left labelled "OK" (used when participants are happy with the colour displayed) and the other on the right labelled "No Colour" (used when stimuli do not trigger a colour experience).

Sequence-space synaesthesia will be confirmed using the method of Ward, Ipser, et al. (2018). This includes both a consistency test and completion of a brief questionnaire. Similarly to the consistency test described above, participants are presented potential synaesthetic inducers (digits [0-9], days of the week [Monday-Sunday] and months of the year [January-December]) but are asked to reproduce the spatial form of the stimuli on a 2D computer screen by making mouse clicks to indicate where each item in the sequence should be placed spatially. Each stimulus is probed three times across the course of the test to test for consistency. Participants also complete the questionnaire designed to accompany the above sequence-space synaesthesia consistency test (see OSF for all questionnaires). We note that by using the questionnaire in conjunction with the sequence-space consistency test, we are better able to discriminate between synaesthetes and non-synaesthetes than through examining cut-off scores from consistency tests alone. By having converging evidence of sequence-space synaesthesia from two sources, we reduce the chances of non-synaesthetes artificially lowering their consistency score through adopting a structured order for stimuli, as has been previously reported when only consistency tests are used (van Petersen et al., 2020).

2.2.2. Visual Stimuli

Stimuli will consist of 224 distinct and identifiable everyday objects from the Bank of Standardised Stimuli (Brodeur et al., 2014). These will be processed using custom R scripts (see OSF for all R scripts). First, images will be converted to greyscale and modified to have a transparent background. Images which are too small (i.e., those that contain more than

120,000 transparent pixels) will be excluded. Using the R package “anticlust” (Papenberg & Klau, 2021), the remaining images will then be categorised on the basis of familiarity and visual complexity before being randomly assigned to four pseudorandom stimuli lists according to task: the practice task list will consist of four objects; the visual perception task list will consist of 45 objects; the short-term memory task list will require 135 objects and be evenly split into one, three and five object memory loads and the long-term memory task list will consist of 45 objects. Each object prompted for recall has a distinct location and colour association which is not repeated over the course of the experiment. All location and colour values are generated by scripts that ensure a wide spread of colour and location values around the circle in each trial and avoid the presentation of similar colours and locations in a sequence within blocks. This is achieved by setting minimum-difference values for both colour and location, as well as jitter.

2.2.3. Questionnaires

Two questionnaires will be administered as secondary measures (covariates of interest, and potential confounds):

Sussex Cognitive Styles Questionnaire (SCSQ). The SCSQ will be used to investigate the visual and verbal processing preferences of participants (Mealor et al., 2016). This is a 60-item questionnaire with six subscales measuring: Imagery Ability; Technical/Spatial Cognition; Language & Word Forms; Need for Organisation; Global Bias; and Systemising Tendency. It incorporates items from a variety of previously validated questionnaires, including the Object Spatial Imagery Questionnaire (OSIQ) (Blajenkova et al., 2006) which is of particular interest in terms of dorsal versus ventral stream visual processing. Respondents rate how much they agree or disagree with an item using a 5-point Likert scale ranging from “strongly disagree” to “strongly agree”.

Situational Motivation Scale. We will assess potential group differences in motivation during the experiment using the self-reported Situational Motivation Scale (Guay et al., 2000).

This is to measure whether individuals with synaesthesia who are recruited from participant databases are more motivated to engage in scientific research than control groups (Simner, 2012; Simner & Bain, 2018). The scale selected is a valid and reliable questionnaire consisting of 16-items which measure situational intrinsic motivation, identified regulation, external regulation, and amotivation. Respondents are asked an overall question of why they are currently engaged in the activity, and rate how well 16 items answer this question using a 7-point Likert scale ranging from 1 *("corresponds not at all")* to 7 *("corresponds exactly")*. For example, a response of "because I think this activity is interesting" may correspond "exactly" to why they are engaged in this activity.

2.3. Procedure

The experiment will be designed and disseminated online using the free, open-source experiment builder lab.js (Henninger et al., 2022). The tasks (visual perception, short-term memory, and long-term memory) will be split across three online testing sessions, with a duration of approximately one hour per session. Prior to completing the tasks, participants will be required to complete a short, separate online screening questionnaire for colour blindness and synaesthesia (the length of which will vary depending on performance in the consistency tests but shall not exceed 30 minutes, see *Section 2.2.1. Consistency Tests*). Session One comprises a video demonstration and practice block, the long-term memory immediate recall task, and a motivation questionnaire. Session Two, which takes place 48-72 hours after Session One, comprises the long-term memory delayed recall task, the visual perception task, and a repeat of the motivation questionnaire. Session Three comprises the short-term memory task and Sussex Cognitive Styles Questionnaire (SCSQ), as well as a final repeat of the motivation questionnaire (see Figure 1 below for an overview of each session and Materials for further details of each task).

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Figure 1

Overview of Test Sessions

Session 1		48-72 hours Session 2		Session 3	
Task	*Duration (mins)*	*Task*	*Duration (mins)*	*Task*	*Duration (mins)*
Full instructions and video demonstration	5	Review Instructions	5	Review Instructions	5
Practice Block	3	Long-term memory (delayed)	15	Short-term memory	45
Long-term memory (immediate)	60	Visual perception	20	Sussex Cognitive Styles Questionnaire	10
Motivation questionnaire	2	Motivation questionnaire	2	Motivation questionnaire	2

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Session 1		48-72 hours Ses	
Task	*Duration (mins)*	*Task*	
Screening Protocol	10	Review Instructions	
Practice Block & View Instructions	5	Long-term memory (delayed)	
Long-term memory (immediate)	60	Visual perception	
Motivation questionnaire	2	Motivation questionnaire	

Note. To identify study eligibility and group membership (synaesthetes, relative, control), prior to completing the test sessions, participants will be asked to complete a short, separate screening questionnaire comprising the colour blindness and synaesthesia tests. Eligible participants will have the option to complete Session One immediately following this, or to return to start the experiment later.

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Session 1		48-72 hours Ses	
Task	*Duration (mins)*	*Task*	
Screening Protocol	10	Review Instructions	
Practice Block & View Instructions	5	Long-term memory (delayed)	
Long-term memory (immediate)	60	Visual perception	
Motivation questionnaire	2	Motivation questionnaire	

To ensure that stimulus size is controlled across screens, at the beginning of each test session participants will be asked to sit an arm's length away from the computer screen (approximately 60cm) and a scaling task is included at the beginning of the experiment such that participants adjust a rectangle to the size of credit card and all stimuli are scaled accordingly to be 5° × 5° of visual angle. All tasks involve an association of object, colour, and location with object acting as the cue. Colour adjustments are made by moving the mouse around a colour wheel underlying the circle. As participants move the mouse around the circle, they see a preview of the changing hue. Participants then click "confirm" when they are

satisfied with the colour they have selected. Location adjustments are made by using the mouse to drag the grey object to the remembered location on the circle and hitting the “confirm” button. Colour and location are chosen sequentially on each trial, with the order of selection (colour or location first) counterbalanced between participants.

In the first session, when participants are familiarising themselves with the overall experiment and need to learn how to submit their answers, there will be a video demonstrating how to report answers using the colour and location wheels, as well as a short practice block, in addition to written instructions. This practice block consists of viewing four different objects in different colours and locations around a circle – in essence, a short version of the long-term memory task described in detail below. These objects are presented sequentially, for two seconds each. Participants are then asked to report the remembered colour and location for each practice object in turn with feedback (see below). Subsequent sessions will begin with a reminder of how to submit colour and location answers, but no practice session.

Participants then complete the main task(s) for each session. The visual long-term memory task will consist of alternating learning and testing phases (three sets of 15 objects, displayed for four repetitions each) prompted for immediate recall, as well as a delayed recall only task 48-72 hours later in Session Two. Session Two contains the visual perception task which will be completed in three blocks of 15 trials (45 objects). The short-term memory task will be completed in Session Three with three blocks of 15 trials, split according to memory load. Block one consists of 15 trials at memory load one (15 objects prompted), block two consists of 15 trials at memory load three (45 objects prompted), and block three consists of 15 trials at memory load five (75 objects prompted).

2.4.1. Long-term Memory Task

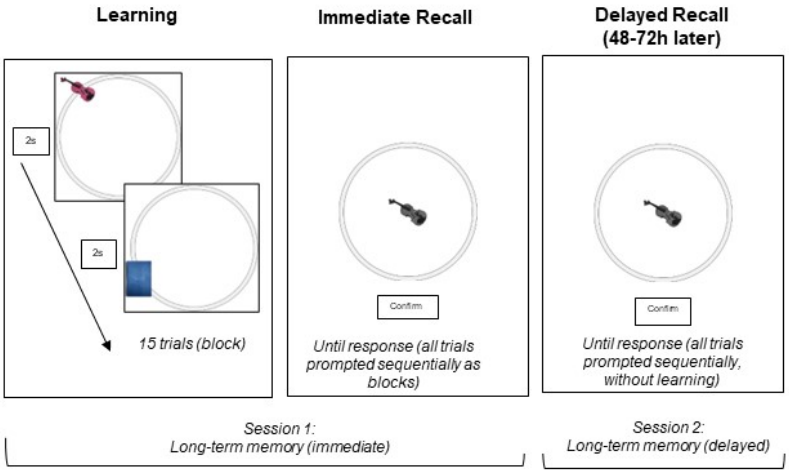
The visual long-term memory task spans two test sessions and comprises repeated learning and test blocks (Session One) and delayed recall (Session Two). Participants are informed at the beginning of the first test session that 45 object-colour-location associations

must be memorised. In Session One, items are divided into three sets of 15 objects to learn, and the participants are presented with each set of objects four times. During the learning phase, each object is sequentially presented in random order for two seconds each. This is followed by a brief retention interval and the immediate recall phase during which the same objects are sequentially presented in random order and probed for colour and location. Participants are given feedback to help them learn during the long-term memory immediate session. After each response, they are presented with a screen for two seconds that uses two stacked sliding visual scales with green "✓" and red "✗" label anchors at each side of the screen. The top scale displays the participants' accuracy for location and the bottom scale displays the participants' accuracy for colour. The scales are non-linear (utilising a square root function of degree of deviation) so that greater space on the scale is dedicated to deviation values between 1-45 degrees than to those between 46-180 degrees. Feedback is shown via a green dot which is placed on the scales between the two labels depending on the deviation from the correct response. At the end of each learning block, participants are also shown their total average deviations from the original colours and locations across the block using the same visual sliding scales. Block feedback is displayed in an untimed manner so that participants can review it for as long they desire before taking a break and moving on to the next learning block.

The second test session, which takes place between 48-72 hours after the first session, will probe for recall of the 45 object associations only, and will not involve learning and immediate recall phases. At the end of each recall block within the long-term memory delayed session (i.e., after each set of 15 objects has been probed), participants will be shown their total average deviation from the original colours and locations (similar to the block feedback they see during the "long-term memory immediate" session).

Figure 2

Long-Term Memory Task Summary



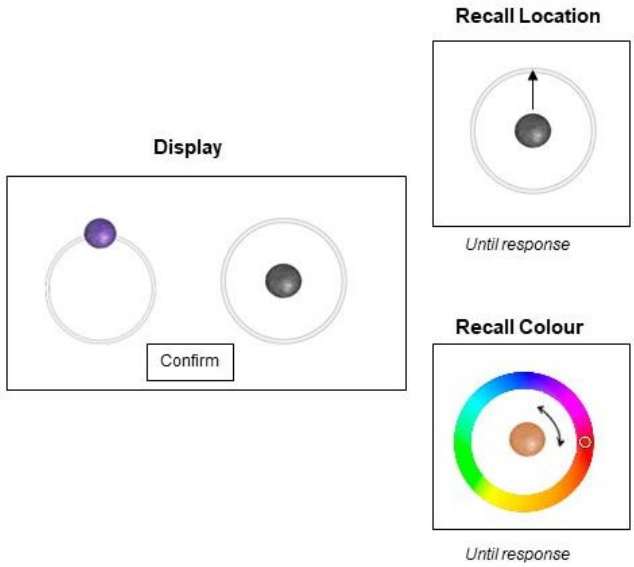
Note. In the long-term memory immediate task, participants are asked to learn colour-location-object associations for 45 objects (split into blocks of 15 objects). These are presented sequentially for two seconds each. Participants report the remembered location and colour as previously and are given feedback about their accuracy. In the long-term memory delayed task, which occurs 48 – 72 hours later, participants only see grey object prompts and are requested to adjust each of the 45 items' location and colour to match its appearance from the long-term memory immediate task.

2.4.2. Visual Perception Task

Participants will be presented with two objects which are identical except for their colour and location: the one on the left acts as a target model, and the one on the right is adjusted to fit the model as accurately as possible (Figure 3). Feedback on average accuracy is provided at the end of each block of 15 objects (not at the trial level) using the same sliding scales as described above.

Figure 3

Visual Perception Example Trial



Note. Participants are asked to adjust the colour and location of the grey object on the right side of the screen to match that on the left. Colour adjustments are made using a colour wheel underlying the circle. To make location adjustments, they use the mouse to drag the grey object to the desired position around the circle.

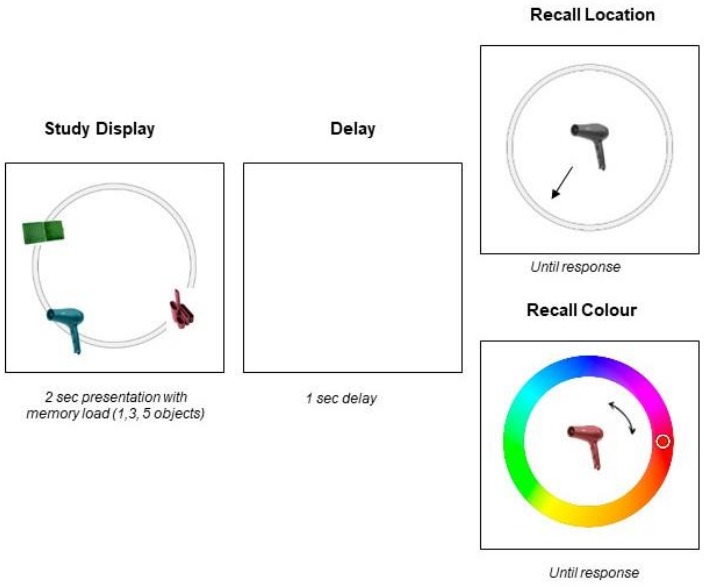
2.4.2. Short-term Memory Task

To measure visual short-term memory performance, either one, three, or five different study objects in different colours at different locations will be presented around a single, central circle. As mentioned, all location and colour values for the short-term memory task have been generated by means of custom R scripts (see OSF) which ensure a wide spread of colour and location values around the circle in three and five load trials while preventing overlap (i.e.,

there is a minimum difference of 50 degrees set between location values in each array). It also avoids the presentation of similar colours and locations in a sequence across trials, including in the one object load condition, by setting minimum differences and enforcing jitter between consecutive trials. The objects in varying load conditions will be presented simultaneously for a duration of two seconds. Following a delay of one second, participants will be cued to recall the colour and location of each object from the array in turn (selected at random). Colour and location adjustments are made in the same way as the other tasks. Feedback on average accuracy is provided at the end of the block (not at the trial level).

Figure 4

Short-Term Memory Example Trial



Note. Either one, three or five objects are presented in different colours at different positions around the circle for two seconds. Following a delay of one second, participants are asked to report the colour and location of each object from the array in turn (selected at random). Adjustments are made analogous to the other tasks.

3. Analysis Plan

In this section, we detail our dependent variables and each of our planned analyses in turn. Please note that model-free analyses are the main source of inference for our hypotheses, and all further analyses (e.g., model-based, Bayesian, multivariate, exploratory) are to be considered secondary but are important with respect to establishing the robustness of findings and in providing supplementary information to aid interpretation (e.g., determining whether null results are sensitive). A table outlining our Analysis Plan and additional information, such as the results of quality assurance and pilot testing, can be found in the Supplementary Materials.

3.1. Dependent variables

Across all tasks, accuracy scores are calculated as the absolute deviation from original colour or location in degrees. Accuracy scores can fall between 0-179 degrees of deviation from the original and are separately calculated for colour and location conditions, with values closer to 0 indicating more precise recall. In the short-term memory task, accuracy scores for location and colour are calculated at three different loads (one, three and five object arrays). In the long-term memory task, accuracy scores for location and colour are calculated for three learning blocks and a final delayed recall block.

3.2. Model-free analyses of accuracy data

3.2.1. Mixed-Factorial ANOVAs

We will conduct a series of mixed-factorial Analyses of Variance (ANOVAs). The first tests the hypothesis that synaesthetes will display enhanced visual perception and memory advantages compared to other groups (i.e., will show greater accuracy across tasks) using the within-subject factor Condition (colour vs. location recall) and the between-subject factor Group (synaesthetes vs. non-synaesthetes) and, as appropriate, the within-subject factor of Array size (short-term memory) or Block number (to assess learning and forgetting rates in long-term memory) [Hypothesis 1]. To investigate whether grapheme-colour synaesthetes and

sequence-space synaesthetes show differential memory and visual perceptual abilities, we repeat the mixed-factorial ANOVAs from above but replace binary Group (synaesthetes vs. non-synaesthetes) with a 2x2 group design based on presence/absence of grapheme-colour and presence/absence of sequence-space (where the 'double absent' group consist of the controls) [Hypothesis 3]. To investigate the pattern of results for relatives, we will enter a third Group (relatives of synaesthetes) in the mixed-factorial ANOVAs above with the within-subject factor Condition (colour vs. location recall) and the between-subject factor Group (synaesthetes vs. relatives vs. non-synaesthetes) [Hypothesis 4].

3.2.2. Correlation Matrix (and Regression Model)

To examine the relationship between performance on perceptual tasks and corresponding memory tasks, irrespective of synaesthesia status, we will conduct correlations between performance measures on the visual perception and memory tasks across all participants considering colour and location separately [Hypothesis 2a]. Given that each memory task has several levels (array size for short-term memory, block number and delay in long-term memory) the levels would be averaged together in the case of a non-significant group X interaction in the ANOVA or treated separately in the case of a significant interaction.

Any significant correlations indicating an association between perceptual precision and memory precision will be explored further in terms of possible confounds that might drive the association, by means of a regression model (with memory acting as dependent variable). Predictors will include perceptual performance (colour or location as appropriate), group status (synaesthesia coded categorically), and other individual difference variables (cognitive styles, motivation, age) [Hypothesis 2b].

3.3. Model-based analyses of Memory Precision and Guess Rate

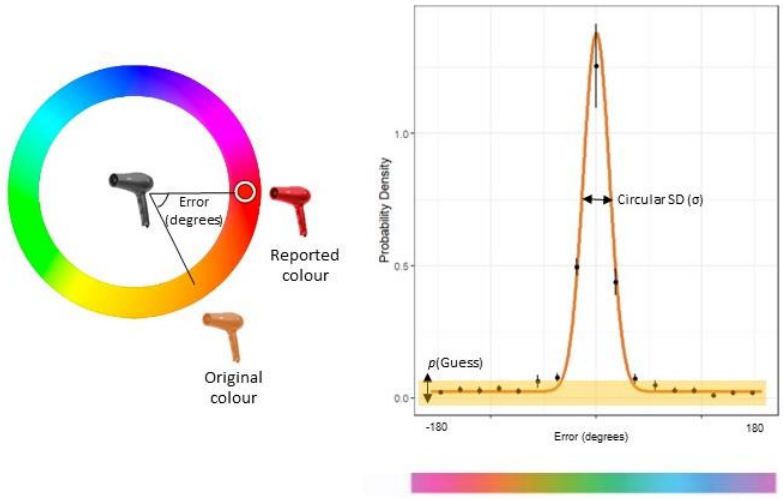
The analyses described above take this entire distribution of responses (centred around the target response at 0 degrees) and calculates the mean. But it is also possible to calculate other derived measures based on a mixture model that assumes that the observed

distribution is made up of several other component distributions: a baseline probability of guessing (modelled as a uniform distribution across all angles), a memory precision score (measured by the error distributions of participant responses) and, in some tasks, memory for a non-target (e.g., if presented a red cup, and blue chair then a cup cue may elicit a blue response which does not reflect a random guess but instead reflects feature-based memory). Precision and guessing will be estimated using the R package mixtur (Grange & Moore, 2022) for all dependent variables and, for the short-term memory task, we will also consider confusion between items (if we have enough trials to do so reliably). See Figure 5 for an illustration of the interpretation of mixture models.

These derived dependent variables will be used to help interpret significant results obtained from the primary analyses as they provide further information about the nature of individual differences in the underlying memory processes. For example, it is possible to have both high memory precision and a high guess rate if a participant learns a small number of items well. Others may learn all associations but only weakly (low precision and low guessing). Enhanced memory would be indicated by high precision and low guessing. (High guessing and very low precision data is likely to be eliminated as outliers due to a failure to engage in the task).

Figure 5.

Examples of Dependent Measure (colour) and the Two-Component Mixture Model



Note. The left image demonstrates the dependent variable in colour space. The absolute deviation of the reported colour from the original colour is measured. The right image shows a two-component mixture model fit to a histogram of response errors, including probability of guessing p(Guess) and the precision of retained memory representations Circular SD (σ).

3.4. Bayesian Statistics

To establish the robustness of our findings, we also utilise Bayesian hypothesis testing to quantify the likelihood of different hypotheses given the data. Here, the evidence level will be set at a Bayes factor of at least 6 times in favour of the experimental hypothesis over the null hypothesis (or *vice versa*, i.e., 1/6). Group differences (examined using ANOVAs in the frequentist approach above) will be assessed using the room-to-move heuristic (Dienes, 2019, 2020) based on a prediction that synaesthetes will outperform controls and the fact that there

is an a priori ceiling on their performance (0 degrees error). That is, the experimental hypothesis will be modelled as a half-normal centred on the control mean with two standard deviations of the distribution defined by the room-to-move (i.e., the difference between the control mean and the ceiling of 0 degrees performance). Testing of regression slopes will be based on the ratio-of-means heuristic (Dienes, 2019, 2020) such that for any pairs of tasks (e.g., colour perception vs. colour long-term memory) a rough scale of effect is determined from a line passing through the mean of the two tasks and the origin.

3.5. Multivariate analyses

Multivariate analyses can detect group differences across multiple variables in a single analysis such that, for example, multiple small effects (with the possibility of being missed in a univariate approach) can collectively constitute a larger overall effect. We perform these analyses to quantify the cumulative impact of multiple factors (e.g., cognitive style subscales, visual perceptual accuracy), gain a deeper understanding of the complex interplay between various cognitive factors and task performance and, using related machine learning techniques, to determine whether relatives have a cognitive profile and task performance that more closely resembles a synaesthetes or an unrelated control participant.

Mahalanobis D is a multivariate effect size that is conceptually equivalent to Cohen's *d* (and gives values on the same scale such that small is $0.3 < d < 0.5$, medium is $0.5 < d < 0.8$, and large is $d > .8$). To calculate Mahalanobis D one needs to know both the univariate effect sizes but also the degree of association between them (correlations). If two variables are measuring the same entity (e.g. r = 1) then the univariate effect sizes are averaged (as occurs in a meta-analysis) but for other combinations the effect sizes are combined according to their degree of dissimilarity (e.g. for two univariate effect sizes of 0.3 and 0.4 where the underlying variables are fully independent, r = 0, then the multivariate effect size is 0.5 based on Pythagarus theorem). Here we shall use all the dependent variables across the tasks and questionnaires to calculate Mahalanobis D comparing the three groups (synaesthetes,

relatives, non-synaesthetes) using the Del Guidice (Del Giudice, 2009) R code with unbiased estimates.

Machine learning is a particular method for transforming multivariate data into a simple univariate data (e.g., classification); for example, generating an AUC (area-under-curve) measure which can also be converted to Cohen's *d*. The approach is to divide the dataset into separate 'train' and 'test' partitions used to develop the algorithm (train) and then use it to predict novel data (test). In this way, machine learning is a predictive approach whereas Mahalanobis D is descriptive. We will use a Random Forest classifier together with 10-fold cross-validation to classify synaesthetes and non-synaesthetes. The classifier can then be used to predict the status of the relatives group which we hypothesise will be intermediate between the groups (see Ward & Filiz, 2020).

3.6. Exploratory Analysis: Impact of Number of Types of Synaesthesia

While the main hypotheses concern the differences between colour and spatial experiences, the number of types of synaesthesia that an individual has may also impact the results (e.g., Ward, Brown, et al., 2018). For exploratory purposes, we will therefore repeat the above analyses (model-free, model-based, Bayesian and multivariate) within the synaesthetes including the number of types of synaesthesia as an independent variable (instead of categorical coding for presence of grapheme-colour and sequence-space). The number of types will fall between one and ten (the maximum possible in the database; see Ward & Simner [2022] for a discussion on synaesthesia grouping). Any effects of the number of types of synaesthesia on results will be reported.

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Supplementary Materials

Table 1

Analysis Plan

	Question	Hypothesis	Sampling plan	Analysis Plan	Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis	Interpretation given different outcomes	Theory that could be shown wrong by the outcomes
1.	Do synaesthetes demonstrate enhanced visual perception and memory advantages compared to non-synaesthetes?	Synaesthetes will display enhanced visual perception and memory advantages relative to non-synaesthetes. Specifically, this should manifest itself as more precision in the choice of colours and locations across multiple tasks (perception, short-term memory, long-term memory).	Power analysis: N=100 synaesthetes N= 100 non-synaesthetic "controls" N = 61 non-synaesthetic "relatives"	Mixed-factorial Analysis of Variance (ANOVA) with the within-subject factor Condition (colour vs. location recall) and the between-subject factor Group (synaesthetes vs. non-synaesthetes) and, as appropriate, the within-subject factor of array size (short-term memory) or block number (long-term memory).	Relevant effect sizes for statistical power analyses were based on effects sizes from Ovalle-Fresa et al. (2021) which uses a similar paradigm. For long-term memory, the value (*d*=0.61) was selected based on a meta-analysis by Ward et al., (2019).	If synaesthetes perform better on both perception and memory tasks, it would support an enhanced perception account as advantages go beyond dual-coding. Co-occurring performance differences across tasks would support representational accounts of memory.	Dual-coding and/or enhanced processing accounts of synaesthesia Representational accounts of cognitive processes.

2a.	Is there a significant correlation between individual differences in performance on perceptual tasks and memory tasks?	Individual differences in performance on perceptual tasks will predict performance on the memory tasks. Specifically, significant correlations should be observed between the precision of perception (of colour and location) and the corresponding visual characteristics when presented in equivalent short-term memory and long-term memory tasks.	As above.	Correlations between performance measures on the visual perception and memory tasks across all participants considering colour and location separately. Given that each memory task has several levels (array size for short-term memory, block number and delay in long-term memory the levels would be averaged together in the case of a non-significant group X interaction in the ANOVA or treated separately in the case of a significant interaction.	As above.	Co-occurring performance differences across tasks would support representational accounts of memory. If these abilities do not co-occur, this may suggest domain specificity for perception and memory processes.	Representational accounts of cognitive processes.

2b.	Do any significant relationships between perception and memory persist when controlling for synaesthesia status and confounding variables such as age, motivation, and imagery?	The significant positive relationship between perception and memory will remain when synaesthesia status and other potential confounds (e.g., age, motivation, imagery) are included in a regression model.	As above.	Any significant correlations relating to the association between perceptual precision and memory precision (directly above) will be explored further in terms of possible confounds that might drive the association, by means of a regression model (with memory acting as dependent variable). Predictors will include perceptual performance (colour or location as appropriate), group status (synaesthesia coded categorically), and our other individual difference questionnaires (cognitive styles, motivation, age).	As above.	As above, but we could additionally interpret results in light of the contribution of motivation (i.e., if confounder, then we would interpret results as artifact of motivation/engagement levels) and imagery (i.e., if confounder, then vivid mental imagery interpreted as critically underpinning performance)	Representational accounts of cognitive processes
3.	Do individuals with grapheme-colour synaesthesia exhibit better memory and	Grapheme-colour synaesthetes will have better	As above.	ANOVA based on hypothesis one but using a 2x2 Group design based on	As above.	If visual perception is better than non-synaesthetes, and the type of	Dual-coding and/or enhanced processing accounts of

	visual perceptual abilities for colour, while those with sequence-space synaesthesia demonstrate better memory and visual perceptual abilities for location when compared to each other and to non-synaesthetic controls?	memory and visual perceptual abilities for colour and sequence-space synaesthetes will have better memory and visual perceptual abilities for location, in comparison to each other and non-synaesthetic controls. Individuals with both types of synaesthesia will show advantages in both tasks.		presence/absence of grapheme colour and presence/absence of sequence space (where the 'double absent' group consist of the controls)		synaesthesia/visual characteristics do not impact results (i.e., all synaesthetes are more accurate to remember both colours and locations), then this would support enhanced processing. If there is a specific enhancement of colour memory, this would support the ventral stream sub-theory in particular. If there are no performance advantages, neither dual-coding or enhanced processing accounts would be supported.	synaesthesia
4.	Do relatives of synaesthetes display a pattern of visual perceptual ability and memory performance more similar to synaesthetes or other non-synaesthetic controls?	Relatives of synaesthetes will exhibit a similar pattern of visual perceptual ability and memory performance as the synaesthetes, albeit intermediate in magnitude. They	As above.	ANOVA with the within-subject factor Condition (colour vs. location recall) and the between-subject factor Group (synaesthetes vs. relatives vs. non-synaesthetes) and, as appropriate, the within-subject factor of array size	As above.	If relatives are more similar to synaesthetes than controls in their performance (and/or are classified as separate from unrelated controls using machine-learning techniques) this would support the view that cognitive differences in synaesthesia comprise an endophenotype.	"Synaesthetic disposition" as an endophenotype

	will outperform non-synaesthetes who are not first-degree relatives of a synaesthete in the perception and memory tasks.	(short-term memory) or block number (in long-term memory). Multivariate analysis and machine-learning (trained on synaesthetes vs. unrelated controls).

Note. For exploratory purposes, we will repeat the above analyses including the number of types of synaesthesia (between 1 – 10) as a covariate. We do not make specific hypotheses for these exploratory analyses.

Supplemental Material 1

Quality Assurance: Splithalf Reliability

We will assess the quality and consistency of all dependent variables by performing split-half reliability assessments on the data using the R package splithalf (Parsons, 2021). This procedure involves randomly dividing the data into 5000 pairs. The averages of the two halves are then compared across the entire sample and the mean correlation (Spearman-Brown) for each dependent variable is reported. Whilst there are no agreed cut-offs for this measure, a higher value (> 0.8) is desired, and the lower the value the harder it is to detect effects of interest. Results from pilot testing (see Table 3 in Supplementary Materials) show good overall reliability in our dependent variable measurement across tasks, as indicated by high Spearman-Brown coefficient values for each task and condition.

Quality Assurance: Absence of Floor and Ceiling Effects

We will check whether floor and ceiling effects are present in our data. To examine floor effects, we will assess whether performance in our most difficult tasks (the short-term memory load five condition and the long-term memory delayed recall block) is above chance. To assess ceiling effects, we will assess performance on the easiest task (visual perception) to see whether participants have perfect performance and refer to prior data on this task.

We did not observe floor or ceiling effects in our pilot test results. In the short-term memory load five task, the results of a one-sample t-test comparing mean deviations to 90 degrees ("chance", as deviation can be between 0 – 179 degrees) for location and colour were both statistically significant ($M_{Location}$ = 51.49, $SD_{Location}$ = 13.17, t(5) = -7.16, p < 0.001; M_{Colour} = 61.40, SD_{Colour} = 9.44, t(5) = -7.42, p < 0.001). Similarly, in the long-term memory delayed recall block, the results of one-sample t-tests comparing mean deviations to 90 degrees for location and colour were both statistically significant ($M_{Location}$ = 24.98, $SD_{Location}$ = 17.17, t(11) = -13.11, p < 0.001; M_{Colour} = 39.49, SD_{Colour} = 25.46, t(11) = -6.87, p < 0.001). These findings indicate that mean performance is significantly different from chance in the most difficult

experimental conditions and therefore an absence of floor effects. In the visual perception task, a one-sample t-test comparing mean deviations to 0 degrees (perfect accuracy) for location and colour were also both statistically significant ($M_{Location}$ = 4.25, $SD_{Location}$ = 2.21, t(14) = 7.44, p < 0.001; M_{Colour} = 6.89, SD_{Colour} = 4.28, t(14) = 6.24, p < 0.001). This shows that performance in the easiest experimental condition is not perfect and therefore an absence of ceiling effects in our task. Additionally, we note that this task has been used in the past (see Ovalle-Fresa et al, 2021) and it was suitable to detect differences on a group level.

Table 2

Summary of pilot testing design

Task	Participants	Design
Visual Perception	N = 5	Three blocks of 15 trials (45 objects).
Short-term Memory	N = 6	Three blocks of 15 trials, split according to memory load. Block one consists of 15 trials at memory load one (15 objects prompted), block two consists of 15 trials at memory load three (45 objects prompted), and block three consists of 15 trials at memory load five (75 objects prompted).
Long-term Memory (immediate recall)	N = 5	Alternating learning and testing phases (three sets of 15 objects, displayed for four repetitions each) prompted for immediate recall.
Long-term Memory (delayed recall)	N = 4	Three sets of 15 objects (as in long-term memory immediate recall above) prompted for delayed recall only 48-72 hours later. Labelled as repetition five.

Notes. All participants were recruited via Prolific and do not experience synaesthesia. Different participants completed each task, with the exception of the long-term memory task where the same participants completed both immediate and delayed recall tasks. One participant completed only the long-term memory immediate recall session, rather than both immediate recall and delayed recall.

Table 3

Summary of results from pilot testing

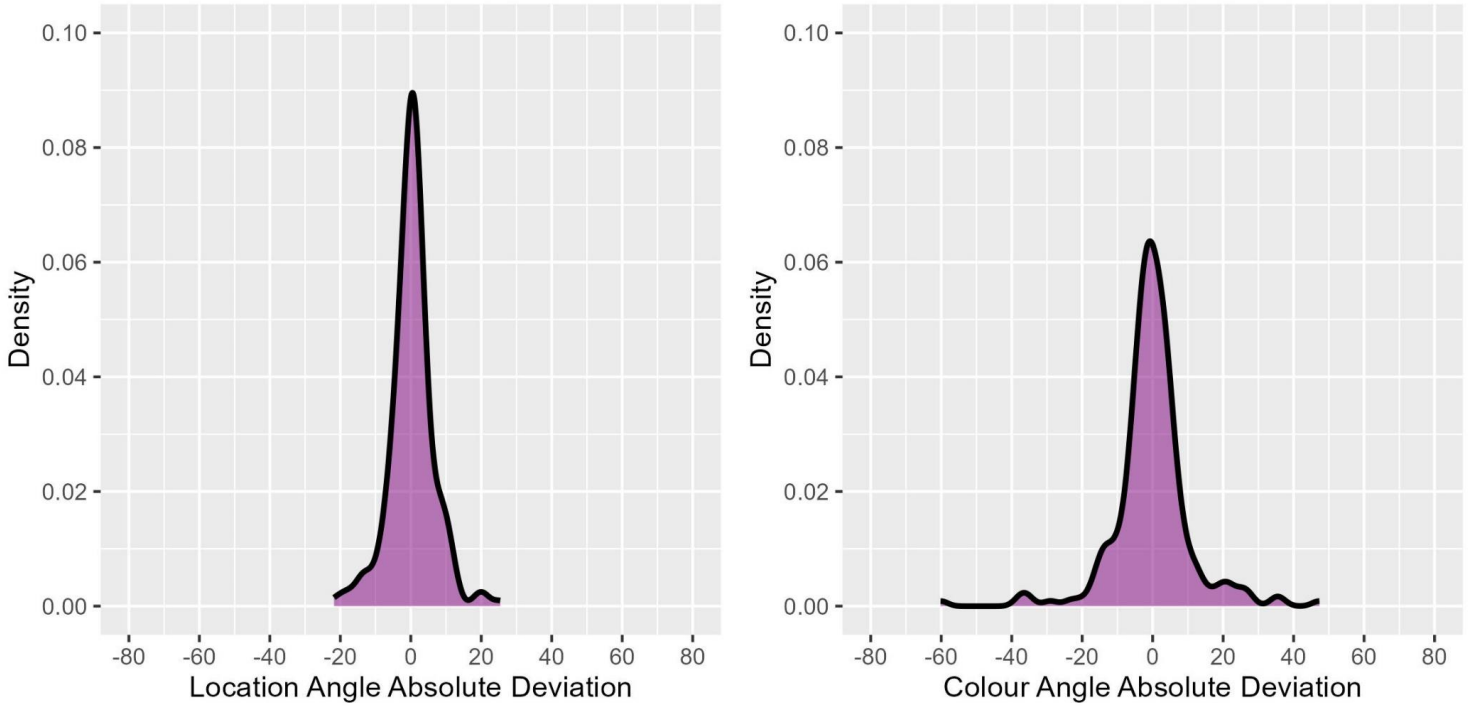
Task	Participants	Analysis	Results (colour)	Results (location)
Visual perception	N = 5	Summary statistics	M = 6.89, SD = 4.28	M = 4.25, SD = 2.21
		Split-half reliability: spearman-brown coefficients	SB = 0.96	SB = 0.95
Short-term memory	N = 6	Summary statistics	For load_n = 1, the mean colour deviation was M = 15.9 (SD = 5.63). For load_n = 3, the mean colour deviation was M = 32.4 (SD = 12.8). For load_n = 5, the mean colour deviation was M = 61.4 (SD = 9.44).	For load_n = 1, the mean location deviation was M = 12.6 (SD = 5.60). For load_n = 3, the mean location deviation was M = 21.3 (SD = 11.2). For load_n = 5, the mean location deviation was M = 51.5 (SD = 13.2).
		Pairwise t-tests	For load 1 vs. load 3, there was a significant difference in mean colour deviation (t = -2.89, df = 6.86, p = 0.02). For load 3 vs. load 5, here was a significant difference in mean colour deviation (t = -4.46, df = 9.19, p < 0.01). For load 1 vs. load 5, there was a significant difference in mean colour deviation (t =	For load 1 vs. load 3, there was no significant difference in mean location deviation (t = -1.70, df = 7.37, p = 0.13). For load 3 vs. load 5, there was a significant difference in mean location deviation (t = -4.28, df = 9.74, p < 0.01). For load 1 vs. load 5, there was a significant difference in mean location deviation (t = -6.65,

			-10.14, df = 8.16, p < 0.01).	df = 6.75, p < 0.01).
		Split-half reliability: spearman-brown coefficients	Load 1 = 0.57 Load 3 = 0.87 Load 5 = 0.62	Load 1 = 0.50 Load 3 = 0.89 Load 5 = 0.83
Long-term memory (immediate recall)	N = 5	Summary statistics	For block 1, M = 65.2, SD = 51.2 For the final block of immediate recall (4), M = 36.1, SD = 33.2	For block 1, M = 49.1, SD = 44.9 For the final block of immediate recall (4), M = 15.8, SD = 16.1
		Pairwise t-test	There was a significant difference in mean colour deviation between the first and last blocks (t = 3.12, df = 27.65, p < 0.01). This is indicative of learning across blocks.	There was a significant difference in mean location deviation between the first and last blocks (t = 4.60, df = 19.70, p < 0.01). This is indicative of learning across blocks.
		Split-half reliability: spearman-brown coefficients	Block 1 = 0.93 Final block (4) = 0.94	Block 1 = 0.94 Final block (4) = 0.96
Long-term memory (delayed recall)	N = 4	Summary statistics	For the delayed recall block (5), M = 39.5, SD = 32.1	For the delayed recall block (5), M = 25.0, SD = 31.1
		Pairwise t-test	There was a significant difference in mean colour deviation between the first	There was a significant difference in mean location deviation between the first block of the

	block of the long-term memory immediate task and the delayed recall block (5) (t = 2.54, df = 24.26, p = 0.02).	long-term memory immediate task and the delayed recall block (5) (t = 2.93, df = 24.40, < 0.01).
	No significant differences were observed between the delayed recall block and any other pairwise comparison (i.e., repetitions 2-4, all p > 0.05). This is indicative of remembering.	No significant differences were observed between the delayed recall block and any other pairwise comparison (i.e., repetitions 2-4, all p > 0.05). This is indicative of remembering.
Split-half reliability: spearman-brown coefficients	Delayed recall block (5) = 0.97	Delayed recall block (5) = 0.88

Figure 1

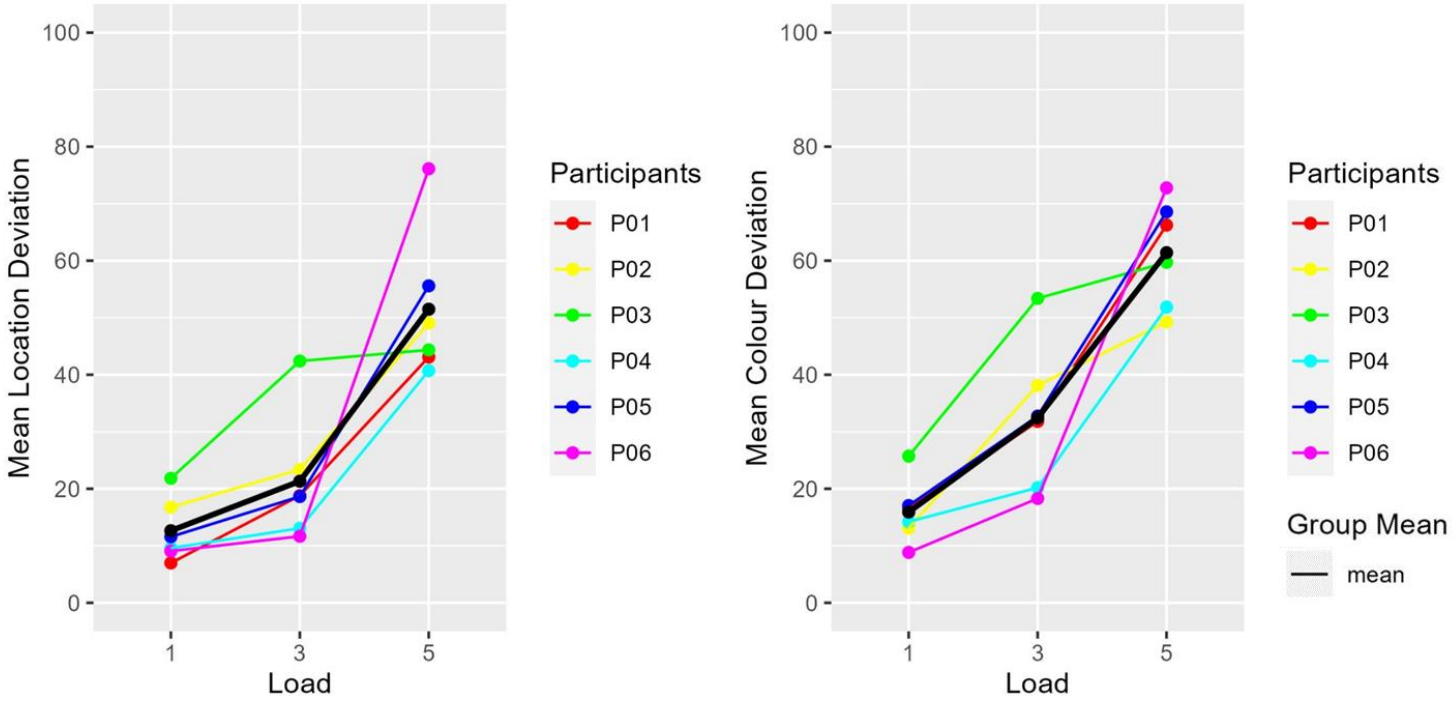
Density plots of results from visual perception task pilot, by condition. Participants are accurate overall but do not show a ceiling effect (i.e. not all responses are at zero).



Note. In the density plots, values closer to 0 indicate more precise recall.

Figure 2

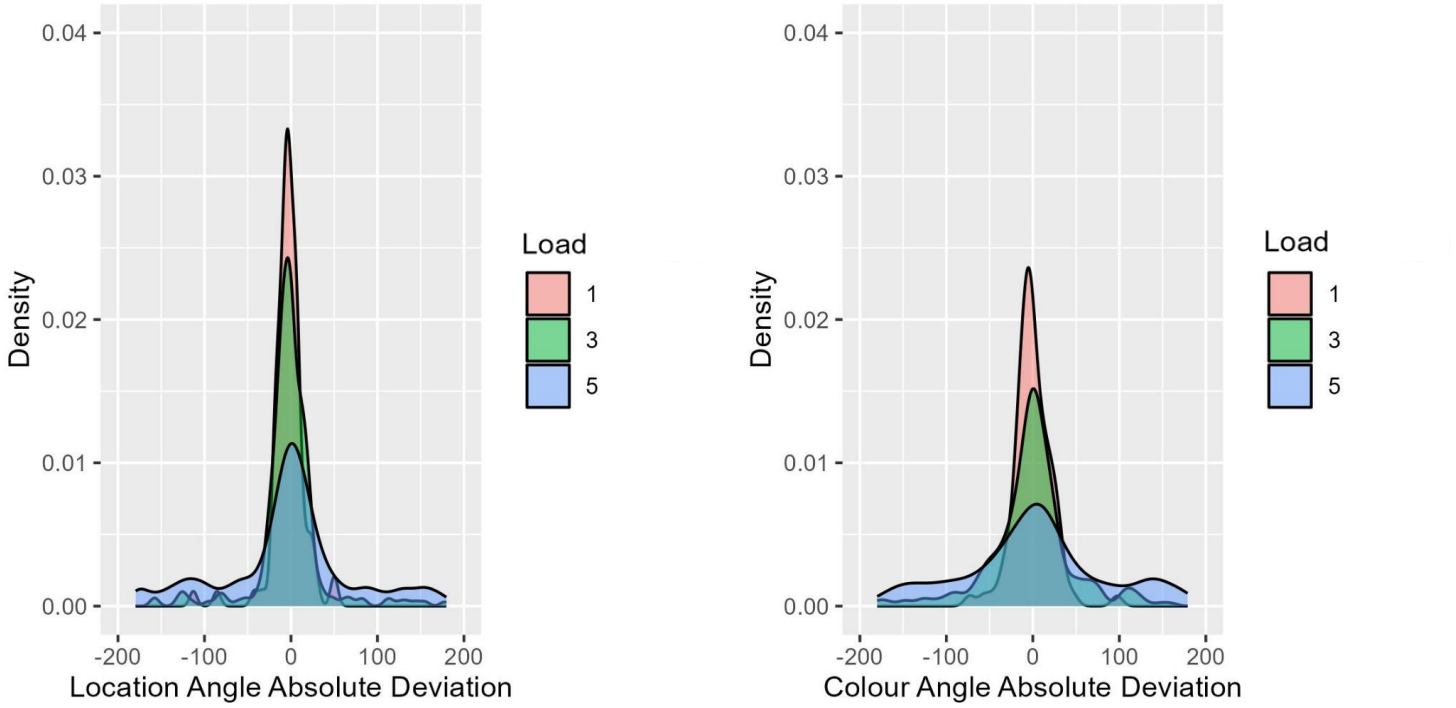
Line graphs showing results from the short-term memory task pilot, by condition



Note. Each participant is referred to by a unique identifier (e.g., P01) and the black line represents the group mean at each load.

Figure 3

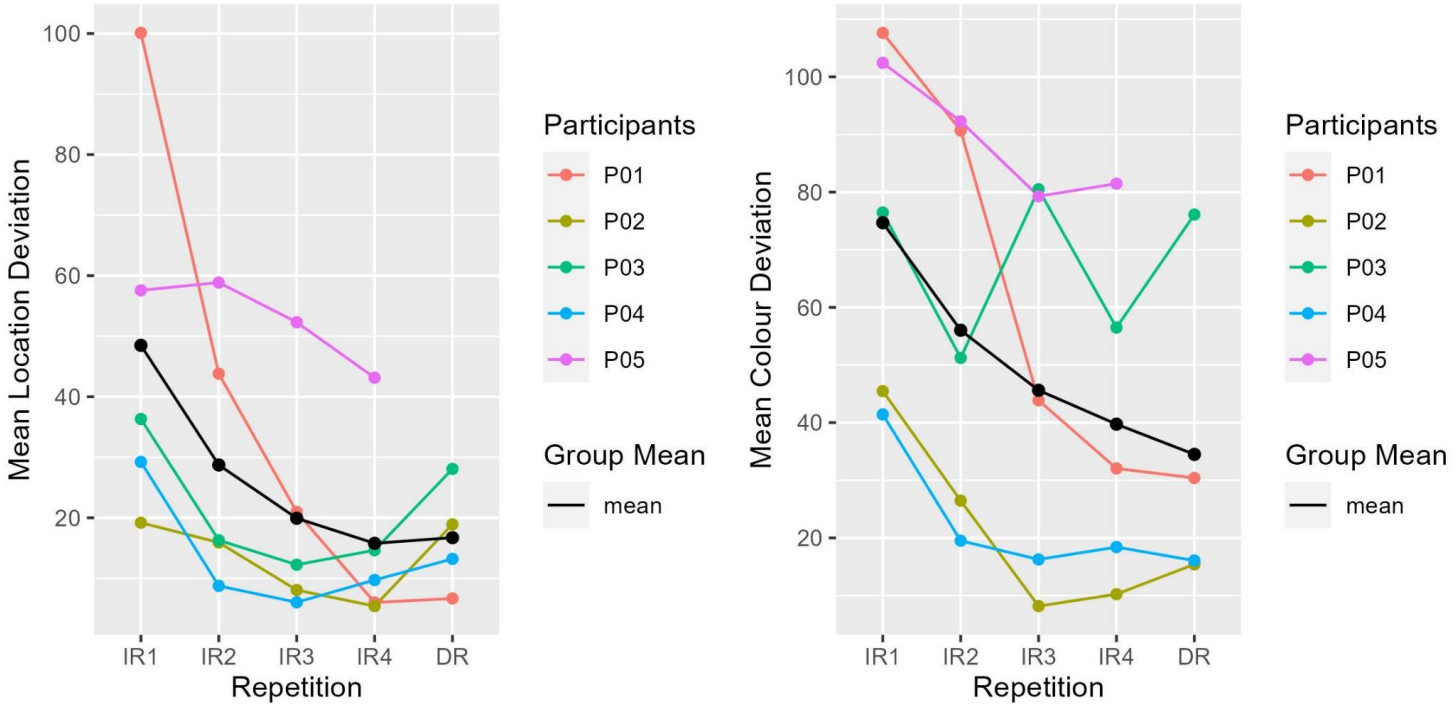
Density plots showing results from the short-term memory task pilot, by condition



Note. In the density plots, values closer to 0 indicate more precise recall.

Figure 4

Line graphs showing results from the long-term memory task pilot, by condition



Note. IR = immediate recall and DR = delayed recall. Each participant is referred to by a unique identifier (e.g., P01) and the black line represents the group mean at each load.