Stage 1 Registered Report

How perceptual ability shapes memory: An investigation in healthy special populations

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Abstract

The enhanced processing account posits a close connection between visual perceptual ability and memory. This account finds support in studies involving special populations with conditions based on neural changes in the ventral visual pathway, such as grapheme-color synesthetes and color experts. Research has shown that, compared to the general population, these groups possess a distinct profile of enhanced perception and memory where they demonstrate better performance in perceiving colors and spatial contrasts, as well as recalling the color of objects (i.e., features that bias the ventral visual pathway). However, complementary predictions of the enhanced processing account regarding special populations with conditions based on neural changes in the dorsal visual pathway, such as sequence-space synesthetes and spatial experts, remain to be explored. This study aims to comprehensively assess the enhanced processing account by testing perception and memory abilities in not only grapheme-color synesthetes and color experts but also in sequence-space synesthetes and spatial experts. These participants will be classified as belonging to either the color domain (encompassing grapheme-color synesthetes and color experts) or the spatial domain (encompassing sequence-space synesthetes and spatial experts). Participants will complete three tasks involving visual perception and visual memory, using color and spatial features to differentiate between the ventral and dorsal pathways. This approach will allow us to examine a double dissociation between domain and feature. That is, according to the enhanced processing account, we hypothesize that grapheme-color synesthetes and color experts will show better performance on tasks involving color features. Conversely, sequence-space synesthetes and spatial experts will show better performance on tasks involving spatial features. Overall, the results of this study will contribute to empirical evidence towards theoretical accounts of perception and memory, suggesting a close connection between perception and memory.

Keywords: Synesthesia, Enhanced processing account, Perception, Memory

Introduction

The enhanced processing account of memory suggests that visual perceptual ability and memory are closely connected (Rothen et al., 2012). This notion is supported by studies with healthy special populations, such as grapheme-color synesthetes and color experts. Grapheme-color synesthesia is a perceptual condition where normal sensory input (e.g., the letter A) triggers additional sensory experiences (e.g., a red color experience). Color-expertise refers to the knowledge, skills and abilities acquired through education and/or experience in processing color information (e.g., artists have color expertise). In line with the enhanced processing account, emerging evidence from different studies has shown that, compared to the general population, grapheme-color synesthetes perform better on tasks involving stimulus features that bias the ventral visual pathway (e.g., better performance for color features of stimuli). However, this enhanced performance is not observed for features that bias processing toward the dorsal visual pathway (e.g., spatial attention; Rothen & Meier, 2009; Yaro & Ward, 2007). Moreover, a more recent study showed that, compared to non-synesthetic control individuals, grapheme-color synesthetes and color experts performed similarly in tasks where stimulus features bias the ventral visual pathway (Ovalle-Fresa et al., 2021). However, this study only examined the predictions of the enhanced processing account on special populations with conditions based on neural changes in the ventral visual pathway (i.e., grapheme-color synesthetes and color experts). Complementary predictions of the enhanced processing account regarding special populations with conditions based on neural changes in the dorsal visual pathway (i.e., sequence-space synesthetes and spatial experts) remain to be investigated. Hence, the primary aim of the current study is to comprehensively investigate the enhanced processing account by not only testing groups with conditions based on the ventral visual pathway, but also groups with conditions based on the dorsal visual pathway.

Grapheme-color synesthesia is the most extensively studied form of synesthesia (Hubbard & Ramachandran, 2005). Research has found that these synesthetic experiences are automatically triggered and are highly consistent over time within individuals, but that the specific associations differ between individuals (e.g., Grossenbacher & Lovelace, 2001; Ward, 2013). One account used to explain the memory advantage in grapheme-color synesthesia is the dual coding strategy account (Paivio et al., 1969) which posits that synesthetic experiences serve as additional retrieval cues. However, this account does not fully explain the memory advantage found in grapheme-color synesthesia, as research has also found that this group experiences memory benefits that extend beyond stimuli inducing synesthetic experiences (e.g., simple abstract figures Rothen & Meier, 2010). Furthermore, not all stimuli triggering synesthesia are better remembered (e.g., recalling the location of digits in a matrix; Rothen & Meier, 2009; Yaro & Ward, 2007).

An alternative account, the enhanced processing account, states that broader changes in the visual system of grapheme-color synesthetes contribute to their memory advantage (Rothen et al., 2012). Indeed, current research findings indicate that the memory advantage observed in grapheme-color synesthesia can be linked to the structural and functional divisions within the human visual system (Barnett et al., 2008). The human visual system can be divided into two distinct pathways, namely the ventral visual pathway (referred to as the "what" pathway) and the dorsal visual pathway (referred to as the "where" pathway). While there is an interaction between processing in both these pathways, the ventral visual system exhibits a bias towards stimuli that encompass high spatial frequency information, high contrast information, color information, as well as visual recognition of elements such as words, objects, and patterns. In contrast, the dorsal visual pathway demonstrates a bias towards stimulus material encompassing low spatial frequency information, low contrast information, achromatic information and motion perception (Derrington & Lennie, 1984; Kaplan, 2001). Interestingly, the memory advantage observed in grapheme-color synesthesia is associated with stimulus material that specifically biases processing within the ventral visual pathway (e.g., Ovalle-Fresa et al., 2021). For example, in grapheme-color synesthesia, memory benefits have been observed for stimulus features consisting of (1) words that evoke synesthetic color experiences while also containing high contrast and spatial frequency information (Gross et al., 2011; Ward et al., 2013), (2) color information that does not induce synesthetic experiences (Lunke & Meier, 2018; Pritchard et al., 2013; Terhune et al., 2013), and (3) simple abstract figures and more complex abstract fractal patterns that are characterized by high spatial frequency information which neither trigger synesthetic experiences nor pertain to the synesthetic domain of color (e.g., Rothen & Meier, 2010; Ward et al., 2013). In contrast, the memory advantage observed in grapheme-color synesthesia is not associated with stimulus material that specifically biases processing within the dorsal visual pathway. For instance, there are no memory advantages observed when considering the position of numbers in a matrix which elicit color experiences but also require spatial attention (Rothen & Meier, 2010; Ward et al., 2013). Similarly, tasks involving location of abstract forms which also require spatial attention do not exhibit memory benefits (Pritchard et al., 2013).

In addition to the memory advantage observed in grapheme-color synesthesia for stimuli that bias the ventral visual pathway, research has also found that grapheme-color synesthesia is associated with enhanced visual perceptual sensitivity for stimuli that bias processing in the ventral visual pathway but not in the dorsal visual pathway (e.g., Banissy et al., 2013; Barnett et al., 2008). Specifically, grapheme-color synesthetes exhibit enhanced visual perceptual sensitivity for high contrast, high spatial frequency, and color information, while showing no enhancement for low contrast, motion, and achromatic information (e.g., Banissy et al., 2013; Barnett et al., 2008). The observed memory advantage and enhanced visual perceptual sensitivity for stimuli that bias processing in the ventral visual pathway align with the emergent memory account (Graham et al., 2010). This account is based on a representational view of memory and perception, suggesting that individual differences in cognitive processes such as visual perceptual ability and visual short-and-long-term memory should be closely related (Graham et al., 2010; Saksida, 2009). The notion that differences in perception and memory are related fits within a broader theory suggesting that the brain is organized to specialize in processing specific types of information (e.g., color versus spatial), and that these specialized regions are used across different cognitive tasks such as perception and memory (Graham et al., 2010). This representational view highlights how the brain processes information, beginning with simple features (e.g., color) in early visual areas, progressing to more complex combinations of features (e.g., individual objects), and culminating in complex visual scenes in the hippocampus at the endpoint of the ventral visual stream.

A study conducted by Ovalle-Fresa et al. (2021) explored the potential association between enhanced visual perceptual ability and enhanced visual memory in grapheme-color synesthesia within a single study. This is important because investigating the potential association between these two abilities within a single study allows for direct comparisons of performance in both, visual perceptual and memory abilities. Additionally, they investigated whether this enhancement extends to a broader population of healthy non-synesthetic individuals. They examined three groups of participants, grapheme-color synesthetes, non-synesthetic color experts (e.g., visual artists), and non-synesthetic controls without color expertise. Each group was assessed in their visual perceptual ability, visual short-term memory, and visual long-term memory for color information. In line with the enhanced processing account, the study found that both grapheme-color synesthetes and color experts share a common cognitive profile, characterized by enhanced visual perceptual ability and memory compared to non-synesthetic controls. This means that individuals with grapheme-color synesthesia and color expertise demonstrate better performance in tasks requiring visual perception and memory, especially those involving color features, indicating enhanced cognitive processing in these areas.

However, investigating only grapheme-color synesthetes and color experts addresses only one aspect of the enhanced processing account. To test this account comprehensively, it is necessary to examine synesthetes and experts with biases in the dorsal visual pathway. Potential candidates for such a study include individuals with sequence-space synesthesia. Sequence-space synesthesia is a well-studied form of synesthesia in which ordinal sequences (e.g., numbers, days of the week, or months of the year) are perceived as occupying specific spatial locations. (e.g., Galton, 1880; Price, 2009; Rothen et al., 2016; Ward et al., 2018). For experts, potential candidates could be individuals with spatial expertise (e.g., architects). According to the enhanced processing account, we should then expect that the visual perceptual and visual memory advantages for spatial features (but not color features) would extend to individuals with sequence-space synesthesia and spatial expertise, just as the advantages for color features are observed in individuals with grapheme-color synesthesia and color expertise.

In the present study, we aimed to investigate both sides of the enhanced processing account by including participants who belong to one of the following groups: grapheme-color synesthetes, sequence-space synesthetes, color experts, and spatial experts. Here, we aim to examine whether the memory and visual perceptual advantages in these groups are directly related to their corresponding feature without generalizing to the other feature. Specifically, grapheme-color synesthesia and color expertise are expected to demonstrate visual perceptual and visual memory advantages for color features (but not spatial features). Conversely, sequence-space synesthesia and spatial expertise are expected to demonstrate visual perceptual and visual memory advantages for spatial features (but not color features). By including both synesthetes and experts, we aim to comprehensively test the enhanced processing account by comparing a synesthetic sample with a non-synesthetic sample that has similar visual perceptual abilities. All participants will perform three versions of the same task: a visual perceptual version, a visual short-term memory version, and a visual long-term memory version. Each version will include two stimulus features: a color feature, which biases processing towards the ventral visual pathway, and a spatial feature, which biases processing towards the dorsal visual pathway.

Based on the enhanced processing account, we expect the following pattern of results (summarized in Supplementary Table 1): 1) grapheme-color synesthetes and color experts (e.g., artists) will exhibit relatively better performance for the color feature compared to the spatial feature, while sequence-space synesthetes and spatial experts (e.g., architects) will perform relatively better for the spatial feature compared to the color feature; 2) Irrespective of group, across all tasks, we hypothesize that participants' perception of color features will significantly predict their memory for color features, and their perception of spatial features will significantly predict their memory for spatial features; and 3) grapheme-color synesthetes and color experts will share a common cognitive profile, where they will perform similarly to each other. Likewise, sequence-space synesthetes and spatial experts will share a common cognitive profile where they will perform similarly to each other.

Methods

Participants

We aim to recruit a minimum of 40 participants for each group: grapheme-color synesthesia, sequence-space synesthesia, color experts, and spatial experts, totaling 160 participants. Each participant will belong to only one group. To ensure 90% power at an alpha level of 0.02 (cf. power analysis) and account for participant exclusions based on performance in the experimental tasks (cf. exclusion criteria), we will increase the total by 30%, resulting in 208 participants, with 52 in each group. If we cannot recruit the ideal number, we will adjust our target to achieve 80% power at an alpha level of 0.05. This requires 80 participants in total, with 20 in each group. Increasing this by 30% gives 104 participants, with 26 in each group. Excluded participants (cf. exclusion criteria) will be replaced to maintain the minimum sample sizes of 40 per group for 90% power or 20 per group for 80% power.

Participants will be divided into two categories: group and domain. Synesthetes will be assigned to the synesthesia group and further categorized into either the color domain (for grapheme-color synesthetes) or the spatial domain (for sequence-space synesthetes). Similarly, experts will be allocated to the expertise group and categorized according to their specific area of expertise, either in the color domain or the spatial domain. All participants will undergo screening to ensure the absence of color blindness.

All participants will be recruited from Prolific (https://www.prolific.co). Ethical approval was received by the internal ethics committee of UniDistance Suisse (application number 2022-05-00001). All criteria pertaining to inclusion and exclusion are addressed at the end of the Methods section, as they are contingent upon a comprehensive understanding of the materials and procedures used in the experiment.

Screening

Participants will be initially screened on Prolific using a screening questionnaire. This questionnaire will include a series of self-report questions designed to identify individuals who experience synesthesia and to assess their hobbies and professions to determine color or spatial expertise. Only participants who report synesthetic experiences and have relevant hobbies or professions indicating color or spatial expertise will advance to the second screening stage. In this second stage, all participants will be required to complete both a grapheme-color consistency test and a sequence-space consistency test.

Sample characteristics determination

Synesthetes will be recruited based on their phenomenological reports, whereas experts will be recruited based on self-reported information about their profession or hobbies. To classify participants as grapheme-color synesthetes or sequence-space synesthetes, all participants will complete a consistency test. Here, we will use the same data-driven approach as Rothen et al. (2013) and Rothen et al. (2016), aiming to optimize the sensitivity and specificity of the cut-off scores for the two consistency tests.

To classify participants as experts, their responses to their profession and hobbies on the screening questionnaire will be used to determine whether they can be categorized as color experts (e.g., artists) or spatial experts (e.g., architects). To determine which hobbies and professions align with color expertise or spatial expertise, we asked ChatGPT (ChatGPT, personal communication, May 28, 2024) to generate some professions and hobbies using the following prompt for color expertise: 'What types of professions and hobbies would give someone color expertise?' (see https://chatgpt.com/share/17d499fa-02b6-4a32-a762-d4724b6b70c0 for a list) and the following prompt for spatial expertise: 'What types of professions and hobbies would give someone spatial expertise? (see https://chatgpt.com/share/7e96feeb-9325-4602-9094-eb2901ab3286 for a list). Subsequently, we will manually review and select participants' hobbies and professions to ensure there is no overlap between the two domains.

To evaluate expertise, two independent researchers will analyze the screening questionnaire responses. They will review participants’ answers to the open-ended questions about their professions and hobbies. In cases where participants can be classified as color or spatial experts, it is expected that the assessments provided by different researchers will exhibit a strong positive correlation, signifying high inter-rater reliability. The reliability of these ratings will be quantified using Cohen’s *kappa* given the nominal nature of the data. A Cohen’s *kappa* value of greater than or equal to 0.6 will be considered indicative of robust inter-rater reliability (McHugh, 2012). If the Cohen’s *kappa* is lower that 0.6, inconsistencies will be discussed among the authors to reach a conclusion on categorizing experts into either the color or spatial domain.

To compare pure groups of experts and synesthetes, we will avoid overlap of scores between the two groups. Participants with overlapping or missing consistency values will be excluded (c.f. Ovalle-Fresa et al., 2021). This exclusion of participants with overlapping or missing consistency values will be carried out after the screening procedure (i.e., these participants will not perform the experimental tasks). We will combine this method with the approaches described above (i.e., phenomenological reports for synesthetes and self-reports of profession and hobbies for experts from the screening questionnaire) to recruit distinct groups of grapheme-color synesthetes, sequence-space synesthetes, color experts, and spatial experts. By recruiting “pure” groups (i.e., participants can only belong to one group and domain), we ensure that participants in one group will serve as controls for the other groups.

Stopping rule

Given that the prevalence of grapheme-color synesthesia is approximately 1.4% in the population (Simner et al., 2006), our goal is to screen at least 5000 individuals on Prolific to establish our subject pool, with the aim of recruiting at least 52 participants in each of the four groups. We will implement a stopping rule where we will pause after every 500 participants to assess their group allocation. Once a group reaches 52 participants, we will stop recruiting individuals who belong to that group as this is when we will have reached our target and would have accounted for any participants who might be excluded. If, however, after exclusions, we lose more than 12 participants in a group, we will continue to target recruitment specifically for the group that has not yet achieved the target sample size. If we have screened 5000 individuals and still not reached our participant goal, we will continue to screen up to 10,000 individuals in batches of 1000.

Materials and apparatus

All tasks, tests, and questionnaires are implemented using labjs (Henninger et al., 2020; https://lab.js.org), which is a free, open-source online study builder. All pre-processing and analyses will be conducted using R version 4.3.1 (https://www.r-project.org). All labjs and R scripts can be accessed on our GitHub (https://github.com/chhavisachdeva/ema_syn_exp_con) and on Open Science Framework (OSF; https://osf.io/vx5zm/). The GitHub repository will be made public following the publication of this paper.

Screening tests material

Screening questionnaire. This questionnaire will include a series of questions designed to determine whether participants self-report phenomenologies of grapheme-color synesthesia or sequence-space synesthesia, or self-report hobbies and professions that classify them as color experts or spatial experts.

Color blindness test. This test will be used to test for color blindness in participants. We will use the Ishihara color blindness test (Clark, 1924) with a total of 21 plates to test for red-green color blindness. We will also use the Farnsworth dichotomous color blindness test (D15: Farnsworth, 1947) to test for other forms of color blindness.

Grapheme-color consistency test. To confirm participants' grapheme-color synesthetic status, we will administer an online consistency test adapted from Rothen et al. (2013). This test will encompass a set of grapheme inducers, including letters of the alphabet (A – Z), digits (0 – 9), days of the week (Monday – Sunday), and months of the year (January – December). For days and months, the first letter will be capitalized. Each grapheme inducer will be accompanied by a circular continuous color palette on the right and a square gradient from white to black positioned in the center of the circular color palette. The hue of each grapheme can be adjusted by using the circular palette with the computer mouse, while saturation and lightness adjustments can be made by moving the computer mouse around the square gradient. The color palette and the luminance scale will comprise of the entire range of colors that can be displayed on a computer screen. Two buttons will be positioned below the circular color palette. The left button will be labelled “OK”, and the right button will be labelled “No Color”.

Sequence-space consistency test. To confirm participants’ sequence-space synesthetic status, we will administer an online consistency test adapted from Rothen et al. (2016). This test will comprise of letters of the alphabet (A – Z), digits (0-9), days of the week (Monday – Sunday), and months of the year (January – December). The font will be Courier New with a point-size of 18 and in bold typeface. For days and months, the first letter will be capitalized.

Visual stimuli

The stimuli will comprise of distinct and identifiable objects from the Bank of Standardized Stimuli (BOSS; Brodeur et al., 2014). This stimuli database consists of a comprehensive collection of 1397 pictorial stimuli. Using the R package *magick* (Ooms, 2023; version 4.8.1), all 1397 images were converted from jpg to png format and were then subsequently converted to grayscale. Using the same package, the images were then given a transparent background and adjusted to red with an opacity of approximately 49. Subsequently, we calculated the number of transparent pixels around each image to determine their size. Then, any image consisting of over 120,000 transparent pixels were removed (n = 491) due to their limited surface for color determination.

The remaining images were then partitioned using the *anticluster* package (Papenberg & Klau, 2021; version 0.8.1) in R (version 4.3.1). Anticlustering was conducted with the aim of achieving high between-cluster similarity coupled with high within-cluster heterogeneity. To do this, the familiarity and visual complexity norms from Brodeur et al. (2014) were used. After removing images which did not contain any values, a total of 586 images remained. Of these 586 images, 118 images will be assigned to the visual perceptual task, 117 images will be assigned to the visual long-term memory task, and 351 images will be assigned to the visual short-term memory task. This was implemented to ensure that each task would consist of a unique set of stimuli with no overlap of stimuli materials between tasks. For all three tasks (visual perceptual, visual short-term memory and visual long-term memory), the number of stimuli per task was based on a split-half reliability analysis (c.f. Supplemental materials). Our goal was to have a Spearman Brown reliability coefficient (r_{SB}) of over 0.7 for each task.

Experimental tasks material

Visual perceptual task. This task consists of two circles situated side-by-side and centered on the screen. Each circle consists of an outer and inner circle. The inner circle is white whereas the outer circle is gray leaving a gray separation between them where the stimulus is situated. The size of the circles and the distance between them are approximately 5° x 5° and 3° x 3° of the visual angle, respectively, at an arm's length distance (approximately 60 cm). The stimuli will have a size of approximately 2° x 2° of the visual angle at the same distance.

In the color feature condition, the outer gray circle on the right represents a color wheel within an HSL (hue, saturation, lightness) color space palette ranging from 0^o to 359^o. The colors for this task consist of a series of 118 different colors sampled around the color wheel. These colors represent approximately every eighth degree equally distributed on the color wheel (cf. procedure section).

In the spatial feature condition, the outer gray circle on the right represents a spatial wheel ranging from 0^o to 359^o. The spatial values for this task consist of a series of 118 spatial values sampled around the spatial wheel. Similar to the color feature condition, these spatial values represent approximately every eighth degree equally distributed on the spatial wheel.

Visual long-term memory task. The materials for the visual long-term memory task are similar to the materials for the visual perceptual task, except for the following changes. First, the visual long-term memory task consists of a single circle situated at the center of the screen. Second, both, the color, and spatial feature conditions will consist of a series of 117 color and spatial values.

Visual short-term memory task. The materials for the visual short-term memory task are similar to those for the visual long-term memory task. However, the short-term memory task will consist of 351 color and spatial values, with a minimum separation of eight degrees and a maximum separation of 120 degrees around the circle.

Questionnaire material

Sussex Cognitive Styles Questionnaire (SCSQ). This is a 60-item questionnaire with each item answered on a 5-point Likert scale ranging from “strongly disagree” to “strongly agree” (Mealor et al., 2016). The questions will be presented in randomized order but will be grouped into six factors for analysis. These factors are imagery ability, technical/spatial cognition, language and word forms, global bias, need for cognition and tendency. This questionnaire incorporates items from a variety of questionnaires including the Object Spatial Imagery Questionnaire (OSIQ) (Blajenkova et al., 2006) which is of particular interest as it differentiates between dorsal versus ventral visual processing.

Strategy Questionnaire. The questionnaire will consist of questions regarding data quality control. This will include questions regarding cheating (i.e., whether they used external strategies like notes to complete the task), the perceived difficulty of the tasks, and the usefulness of the feedback provided during the tasks. We will also ask them to confirm whether we can use their data for publication purposes.

Procedure

First, we will pre-screen participants on Prolific using a screening questionnaire to establish a subject pool. Completion of the questionnaire will require a maximum of 5 minutes, and participants will be compensated GBP 0.75 for their time.

Once our subject pool is established, we will invite participants from it to complete the experiment, which will comprise of six online sessions spanning six days (see Table 1). In the first session, all participants will complete the demographic questionnaire, the Ishihara color blindness test, the Farnsworth dichotomous color blindness test, the grapheme-color consistency test, and the sequence-space consistency test. In the next five sessions, participants will engage in the three task versions used to assess visual long-term memory, visual perception and visual short-term memory (Brady et al., 2013). All participants will perform these three tasks in the sequence outlined above. This sequence is necessary because seven days are required between the two phases of the visual long-term memory task (see Table 1). During this interval, other tasks cannot be presented as they might interfere with the encoding and retrieval processes of the visual long-term memory task. In all three tasks, visual perceptual, visual short-term memory, and visual long-term memory, the sequence of the color and spatial feature conditions will be counterbalanced between participants. One group of participants will complete the spatial feature condition first, followed by the color feature condition, while the other group will complete these conditions in the reverse order. Furthermore, the counterbalancing condition for the two features will remain consistent for all participants across all tasks. In addition, in all three tasks, the color wheel will rotate on every trial to ensure that the same color does not appear in the same position on the circle each time. Instead, it will appear in different positions on the circle on every trial. Each session will last

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Table 1

Session number / Day	Tasks or questionnaires
Session 1 Day 1	1. Color Blindness Test – Ishihara Color Blindness Test 2. Color Blindness Test – Farnsworth Dichotomous Color Blindness test 3. Grapheme-Color Synesthesia Consistency Test 4. Sequence-Space Synesthesia Consistency Test
Session 2 Day 2	1. Visual Long-Term Memory Task Study Phase Day 1 2. Strategy Questionnaire
Session 3 Day 3	1. Visual Long-Term Memory Task Study Phase Day 2 2. Strategy Questionnaire
Session 4 Day 4	1. Visual Long-Term Memory Task Study Phase Day 3 2. Strategy Questionnaire
Session 5 Day 11	1. Visual Long-Term Memory Task Test Phase 2. Visual Perceptual Task 3. Visual Short-Term Memory Task Load 1 4. Strategy Questionnaire
Session 6 Day 12	1. Visual Short-Term Memory Task Load 3 2. Visual Short-Term Memory Task Load 5 3. Strategy Questionnaire 4. Sussex Cognitive Styles Questionnaire

Note. Table depicting the overview of the different sessions and different days. Notably, session five will take place one week after participants complete the three study phases for the visual long-term memory task.

approximately 60 minutes and participants will receive reimbursement of GBP 9 per session for their time.

In each session, we will first obtain written consent from each participant and explicitly inform them of their right to withdraw from the study at any point. Subsequently, in each session, participants will follow the same sequence of first performing the scaling task (cf. below for a more detailed description), and then viewing the task instructions. Following the task instructions, participants will complete a short multiple-choice comprehension quiz designed to assess their understanding of the various task components. For each incorrect response, participants will receive additional clarification regarding that specific task element. This will be done to ensure that participants are confident in their knowledge of what to do in the task before beginning the task. At the end of each session, participants will complete the scaling task once again and they will also complete the strategy questionnaire. After completing all sessions, participants will complete the Sussex Cognitive Styles Questionnaire.

Scaling Task. To ensure consistent stimulus size for all participants, we will administer a scaling task both before and after each of the sessions. In this task, participants will be instructed to adjust the size of a rectangle to match that of a standard credit card, ensuring uniformity of stimulus size. The scaling task will be conducted twice for each session, with the second iteration occurring at the end of the session. The initial size of the rectangle differs between the scaling tasks conducted at the beginning and end of each session. This will be done to confirm participants' accurate adjustment of stimulus sizes and prevent participants from simply clicking through the scaling task. To assess this, the ratio between the two scaling tasks in each session will be computed. Thus, a ratio of 1 would indicate perfect correspondence. All tasks outlined below will consist of scaled stimuli.

Color blindness tests. For a more comprehensive color blindness testing routine, participants will be asked to complete two color blindness tests, the Ishihara color blindness test (Clark, 1924) which mostly captures red-green color blindness, and the Farnsworth dichotomous color blindness test (D15: Farnsworth, 1947), which captures the ability to discriminate between different hues and identify their order correctly. In the Ishihara color blindness test, participants will see 21 Ishihara plates each containing a number. For each of the plates, participants will be asked to input the number that they see in the text box below the plate. If participants see nothing, they will be instructed to input "0". Participants will be awarded one point for each correct response. A total score of less than 17 out of 21 will be used to identify red-green color blindness. In the Farnsworth dichotomous color blindness test, participants will be asked to arrange 15 colored squares in the correct order by selecting the choice most similar to the previous color. This test evaluates color vision deficiencies and discriminative abilities. In this color blindness task, a total score of less than 13 out of 15 will be used to identify color vision deficiency.

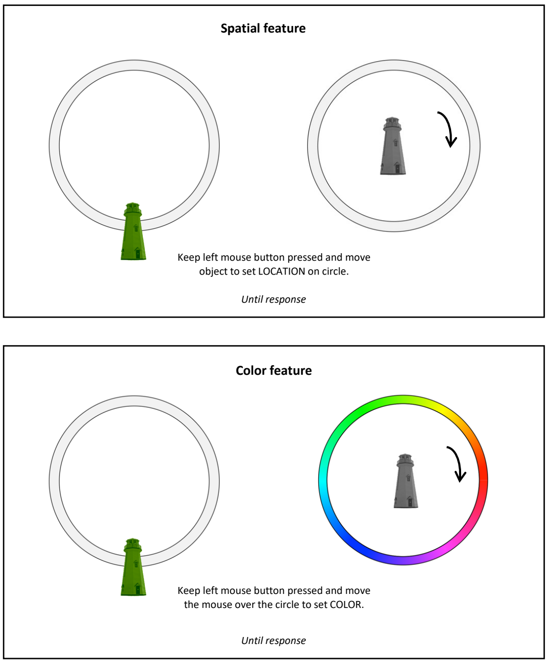
Grapheme-color consistency test. In this task (c.f. Rothen et al., 2013), participants will be presented with inducer graphemes such as letters of the alphabet, digits, days of the week, and months of the year, presented individually in randomized order. These inducers will be displayed on the left of a continuous color palette. Participants will be instructed to use the circular color palette to adjust the hue of each inducer, and the square gradient to adjust the saturation and lightness of the presented inducer. They will also be asked to make use of the "No color" option if no color is associated with an inducer. After all inducers are presented, participants will be told that the first round of the test has been completed. They will then complete a brief quiz regarding their synesthetic experience before completing the second round of the consistency test. A total of 55 stimuli will be presented in each round.

Sequence-space consistency test. In this task (c.f. Rothen et al., 2016), participants will be presented with stimuli inducers such as letters of the alphabet, digits, days of the week, and months of the year, presented individually in randomized order at the center or the screen. Participants will be asked to select a spatial location for each presented stimulus by clicking with the mouse on a chosen position on the screen. Participants will also be instructed to use the screen as a reference frame for intuitively placing stimuli in different spatial locations. If a stimulus does not induce any synesthetic experience, participants will be instructed to press the space bar, which will lead to the next stimulus without requiring them to decide on a location. After all inducers are presented, participants will be informed that the first round of testing has been concluded. They will then complete a brief quiz regarding their synesthetic experience before proceeding to the second round of the consistency test. A total of 55 stimuli will be presented in each round.

Visual perceptual task. In this task, participants will be presented with two adjacent circles (see Figure 1). An image will be displayed on the outer gray left circle (i.e., target) and participants will have to match the color and spatial location of the image presented on the right circle (i.e., probe) with the target image as closely as possible. In the spatial feature condition, participants will have to match the spatial placement of the probe to the target as precisely as possible by moving their computer mouse around the right circle. In the color feature condition, participants will have to match the color of the probe to the target color as precisely as possible by moving their mouse around the right circle. Each trial will consist of sequentially completing both the spatial feature condition and the color feature condition. In other words, the spatial and color feature conditions are nested within trials. In both spatial and color feature conditions, participants will be able to progress to the next trial by clicking the "Next" button when they are satisfied with their response. However, in the spatial feature condition, the “Next” button will only appear when the image is on the outer gray circle. In total, participants will complete 4 practice trials and 45 experimental trials of this task.

After each trial, participants will receive feedback on their performance on that trial. This feedback will be presented visually through two scales – one for accuracy in the spatial feature condition and the other for accuracy in the color feature condition. On these scales a smiling face will be positioned at the left end signifying perfect performance where there is an absolute color or spatial feature deviation of 0 degrees between the probe and the target.

Figure 1



Note. Schematic depiction of the visual perceptual task. Participants are asked to match the color and spatial location of the gray image on the right side of the screen to the image on the left. To match the spatial location, participants use their mouse to drag the gray image to the correct position around the circle. To match the color, participants use their mouse to drag the cursor around the circle, which changes the color of the image on the right. The color wheel is intended for illustration purposes only and will be displayed in gray during the task, as shown in the upper part of the image.

Conversely, a frowning face will appear at the right end of the scale signifying poor performance where there is an absolute color or spatial feature deviation of 180 degrees between the probe and the target. Each scale will consist of a marker in the form of a green circle. The placement of this circle on the scale will correspond to the degree of deviation in participants' responses from the correct color or spatial location. Greater deviations in performance will shift the circle towards the right side of the scales (closer to the frowning face) while lower deviations in performance will shift the circle towards the left side of the scale (closer to the smiling face). During the practice trials, feedback will be untimed where participants will be presented with a "Next" button on the feedback screen to proceed to the next trial. This will be done to ensure that participants have enough time to understand the feedback given. During the experimental trials, feedback will be presented for 2000ms before continuing to subsequent trial.

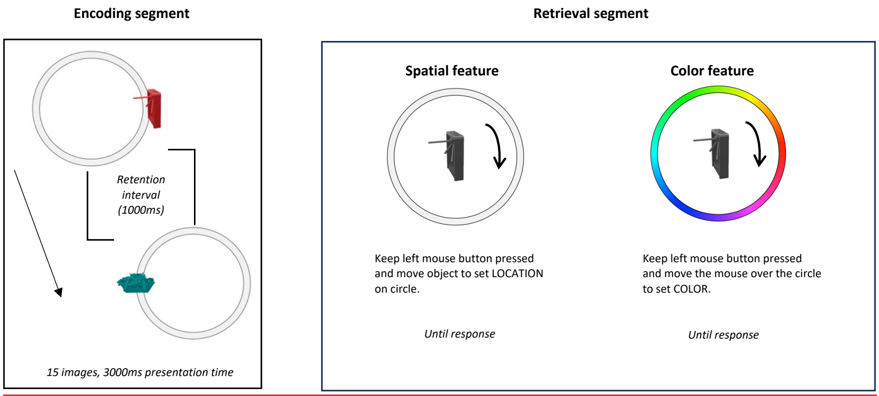
Among the 118 stimuli used for this task, four will be assigned to the practice trials. For each of these four images, a color and spatial location value (0^o, 90^o, 180^o, and 270^o) is equidistantly sampled along a color and spatial wheel. On the practice trials, the stimulus participants receive, and its corresponding color and spatial location value will not be randomized. After completing the four practice trials, participants will engage in three blocks of 15 trials for the visual perceptual task. For the experimental trials, each participant will be presented with 45 stimuli randomly chosen (without replacement) from the remaining 114 stimuli, after the exclusion of the practice stimuli. Similarly, for the color and spatial location values, each participant will be presented with a random selection (without replacement) of 45 values, ensuring a minimum separation of at least eight degrees between each value. A demonstration version of the visual perceptual task can be accessed here: https://memcog.fernuni.ch/studies/perceptual_demo/.

Visual long-term memory task. The visual long-term memory task will be divided into two phases: the study and test phase. The study phase will span three sessions that will be performed on three consecutive days. Each session will consist of an encoding segment followed immediately by a retrieval segment.

In the encoding segment, participants will sequentially view a total of 45 target images in different colors and spatial locations around a circle, with each image presented for 3000ms (see Figure 2). These target images will be divided into three sets of 15 images each, where participants will need to encode both the color and spatial location of each image in preparation for the subsequent retrieval segment. Participants will repeat each set twice, encoding and retrieving each set of 15 images two times (i.e., two repetitions). During the encoding segment, each target image will be presented in random order, followed by a brief retention interval of 1000ms before the next target image is presented. The 45 images and their corresponding color and spatial associations will remain the same across all three sessions. Consistently presenting the same stimuli with their specific color and spatial associations across all three sessions is crucial for learning in the visual long-term memory task.

The retrieval segment will immediately follow the encoding segment. During this segment, participants will be presented with the same target images, now as probes, in random order. They will then be asked to recall the color and spatial location of each image to the best of their ability. Each trial will involve sequentially completing both the spatial feature condition and the color feature condition for one probe. To submit their chosen color and spatial

Figure 2



Note. Schematic depiction of the study phase of the long-term memory task. Participants will learn the color and spatial features of 45 stimuli, divided into three sets of 15 stimuli each, during the encoding segment. Each of the 15 stimuli is presented sequentially for 3000ms. After the encoding segment, participants will report the color and spatial features they encoded. To adjust the spatial feature, participants use their mouse to drag the gray image to the correct position around a circle. To adjust the color feature, participants use their mouse to drag the cursor around a circle, changing the color of the image. The color wheel is intended for illustration purposes only and will be displayed in gray during the task.

location, participants will click the “Next” button, which will also advance them to the next trial. In the spatial condition, the “Next” button will only appear once the image is on the outer gray circle.

After each repetition, participants will receive feedback on their performance. This feedback will be presented similarly to the visual perceptual task, but with the green dot now representing participants' average performance on each repetition. During practice trials, the feedback will be untimed, and participants will be presented with a "Next" button on the feedback screen to proceed to the next trial. In the experimental trials, feedback will be displayed for 2000ms before proceeding to the subsequent trial.

Before starting the experimental trials, participants will complete a set of practice trials. In these practice trials, participants are required to encode and retrieve the color and spatial location of four target images. Participants will only complete the practice trials in the first session (i.e., on the first day). Among the 117 stimuli, four will be assigned to the practice trial. As in the visual perceptual task, for each of the four images a color and spatial value (0^o, 90^o, 180^o, and 270^o) is equidistantly sampled along a color and spatial wheel. As before, on practice trials, the stimulus participants receive, and its corresponding spatial and color value will not be randomized.

For the experimental trials, two lists of 45 stimuli will be created from a pool of 113 stimuli, excluding practice stimuli. Additionally, for the color and spatial feature conditions, two lists of 45 values will be generated, ensuring a minimum separation of eight degrees between each value on the color and spatial wheels. Each image will be paired with a corresponding color and spatial value. Participants will receive one of the two counterbalanced lists, with stimuli presented in random order. A demonstration of the study phase of the visual long-term memory task can be found here: https://memcog.fernuni.ch/studies/ltm_demo/.

The second phase of the visual long-term memory task, the testing phase, will take place one week after participants complete the study phase. During this phase, participants will be presented with all 45 probe images, shown in grayscale and centered in the circle. Their task will be to recall the color and spatial features associated with each probe from the study phase. The probe images will be presented in random order without replacement. All other aspects of the testing phase, such as how to provide responses, will be the same as the retrieval segment of the study phase.

Visual short-term memory task. In this task, participants will be instructed that they will be presented with different images (i.e., targets) in different colors and spatial locations and that their objective is to memorize these targets along with their corresponding spatial location and color for a subsequent recall test (see Figure 3). Participants will be presented with images in loads of one, three and five. These three load conditions will be divided into three blocks where participants will first complete trials of load one in the first block, then load three in the second block and finally, load five in the third block. The number of stimuli presented in each load will be kept constant at 45, so participants will be presented with a total of 45 stimuli in each of the three loads. Therefore, there are 45 trials in load one, as participants need to encode and recall the color and spatial features of 45 individual stimuli. In load three, there are 15 trials, as participants need to remember the color and spatial features of three images presented simultaneously on each trial (45 images / 3 images per trial = 15 trials). Finally, in load five, there are nine trials, as participants need to remember the color and spatial features of five images on each trial (45 images / 5 images per trial = 9 trials). At the start of each block, participants will complete one practice trial to familiarize themselves with the working memory load of that block.

The first block involves encoding and retrieving the spatial location and color of a single image (i.e., load one). Participants will view this image displayed on a circle positioned at the center of their screen, similar to the visual long-term memory task. This image will be presented for 3000ms, followed by a retention interval for 1000ms. Subsequently, the same image will be presented as a probe in grayscale at the center of the circle (i.e., retrieval segment), and participants will be asked to retrieve the color and spatial location (in sequence) of the image to the best of their ability. To submit their chosen spatial location and color, participants will click on the "Next" button to advance to the next probe. In the spatial condition, the "Next" button will only appear once the image is on the outer gray circle.

After completing the first block, participants will proceed to the second block with a load of three (albeit the next day). In this block, participants will have to encode and retrieve the color and spatial location of three images presented simultaneously during encoding. Each of these images will be presented in distinct colors and spatial locations on a circle. Like the previous block, these images will be presented for 3000ms. Subsequently, each image will be displayed individually in grayscale at the center of the circle. Participants will then be probed for the color and spatial location association of each image in randomized order, and will be

Figure 3

Note. A schematic depiction of the short-term memory task. Participants are presented with stimuli in different colors and locations around a circle for 3000ms. They will see a) one image in the load one condition, b) three images in the load three condition, and c) five images in the load five condition. After viewing the images, participants will have a retention interval, after which they must retrieve the color and spatial features of the images they just encoded. To adjust the spatial feature, participants use their mouse to drag the gray image to the correct position around a circle. To adjust the color feature, participants use their mouse to drag the cursor around a circle, changing the color of the image. The color wheel is intended for illustration purposes only and will be displayed in gray during the task.

asked to retrieve these to the best of their ability. As before, a chosen spatial location and color will be submitted by clicking the "Next" button which will also initiate the next probe.

The final block will consist of a load of five. This block will follow the same sequence as the first and second blocks, except that each encoding trial will consist of five images presented simultaneously in different colors and spatial locations on a circle. The retrieval segment will be the same as the previous blocks where each image will be displayed individually in grayscale at the center of the circle and participants will be probed for the color and spatial location association of each image. As before, images will be presented in randomized order in the retrieval segment.

Among a total of 351 stimuli, 117 stimuli will be assigned to each of the three load conditions. Among its respective stimuli pool, one stimulus will be assigned to the practice trial of load one, with color and spatial location values set at 90°. For the practice trial of load three, three images from this load's respective stimuli pool, will be assigned with color and spatial values sampled at 0°, 120°, and 240°. Finally, for the practice trial of load five, five images from this load's respective stimuli pool, will be assigned with color and spatial values sampled at 0°, 72°, 144°, 216°, and 288°.

During the experimental trials, each participant will be presented with 45 stimuli randomly selected (without replacement) from the remaining pool of stimuli in each load condition's respective stimuli pool, after excluding the practice stimulus (i.e., 116 for load one, 114 for load three, and 112 for load five). Similarly, for color and spatial location values, each participant will be presented with a random selection (without replacement) of 45 values in each load condition. In load one, a minimum separation of at least eight degrees between each value will be ensured. For load three, the minimum separation between the three presented images will be 50 degrees, and for load five, it will be 40 degrees between the five presented images. The wider distance in load three and five conditions aims to sample a more diverse selection of color and spatial location values while preventing physical overlap of images on the circle when presented simultaneously. For all loads of the visual short-term memory task, the starting point for the stimulus positions on the wheel will be randomly generated.

Participants will receive performance-based feedback after completing each trial. This feedback will be the same as that presented in both the visual perceptual and visual long-term memory tasks where participants' performance is symbolized by a green dot on a scale ranging from perfect performance (depicted as a smiling face) to poor performance (depicted as an angry face). In the first block, where the memory load is one, the green dot will represent participants' absolute angular deviation from the original color and spatial location on that specific probe (as in the visual perceptual task). In the second and third blocks with memory loads of three and five respectively, the green dot will indicate participants' average absolute angular deviation from the original colors and spatial location of all probes presented on the preceding trial (as in the visual long-term memory task). A demonstration version of the visual short-term memory task can be accessed here: https://memcog.fernuni.ch/studies/stm_demo/.

Inclusion and exclusion criteria

Inclusion criteria for participation are as follows: individuals must be aged between 18 and 40 years old, have normal or corrected-to-normal vision, and be from the United States or the United Kingdom to ensure sufficient English language proficiency for comprehending task instructions and questionnaires. Critically, all participants who only belong to one of the four groups (grapheme-color synesthetes, sequence-space synesthetes, color expert or spatial expert) will be invited to proceed with the diagnostic tests (i.e., color blindness and consistency tests). Moreover, only participants without missing and overlapping values in the consistency tests, who successfully complete the diagnostic tests, and meet the criteria to be classified into one of the four groups will be invited to participate in the experimental tasks.

Participants who are invited to and complete the experimental tasks will be excluded if they satisfy any of the following criteria: 1) a value of less than 17 out 21 correct in the Ishihara color blindness test or a value of less than 13 out of 15 correct in the Farnsworth dichotomous color blindness test; 2) if the ratio between the dots per inch (dpi) derived from the first and second scaling tasks is more than 3 median absolute angular deviation units (MAD; Leys et al., 2013); 3) They are multivariate outliers in accuracy across all three tasks (visual perceptual, visual short-term memory, and visual long-term memory) using the Mahalanobis-MCD method

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(Leys et al., 2018) for each feature condition (color and spatial); and 4) if more than 50% of their data is missing in the scaling task, visual perceptual task, short-term memory task or the long-term memory task.

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Design and analysis

Design

Overall, this study will employ a 2 x 2 x 2 mixed design, including the between-subjects factor Group (synesthesia versus expertise), the between-subjects factor Domain (color versus spatial), and the within-subjects factor Feature (color versus spatial). In this study, each version of the task will be analyzed separately, resulting in the visual short-term memory version to be extended by the within-subjects factor Load (one, three, and five), and the study phase of the visual long-term memory version to be extended by the within-subject factor Day (one, two, and three).

In all three tasks, the dependent variable is the absolute angular deviation from the original color or spatial location in degrees. This value ranges from 0 to 180 with values closer to 0 indicating more precise recall.

Planned analyses

All statistical tests will be two-tailed. If we can acquire our target number of synesthetes (cf. power analysis below) on Prolific, we will use an alpha value of .02 for all statistical tests (in accordance with the author guidelines of Cortex, the first journal to introduce registered reports in psychology in 2013). However, if the number of synesthetes we acquire is lower than our target, we will use an alpha value of .05 for all statistical tests. In the color feature condition for all tasks, HSL color values will be converted and saved as CIELuv color values for analysis. This is because measured Euclidean distances in CIELuv color space provide approximate estimations of perceptual color differences, improving its accuracy (c.f. Rothen et al., 2013). In the next sections, the planned analyses are outlined below.

In our first hypothesis, we predict that: 1) grapheme-color synesthetes and color experts will perform relatively better in the color feature condition than in the spatial feature condition; and 2) sequence-space synesthetes and spatial experts will perform relatively better in the spatial feature condition than in the color feature condition. To test this hypothesis, we will conduct a series of linear mixed models across the three tasks using the *lme4* package (Bates et al., 2015; version 1.1.35.1) in R on the dependent variable.

An overview of the models for each task is depicted in Table 2. For all linear mixed models, the selection of the random-effects structure (including intercepts and slopes) will

Table 2

	Visual Perceptual Task	Visual Short-Term Memory Task	Visual Long-Term Memory Task (Study Phase)	Visual Long-Term Memory Task (Testing Phase)
Design	2 x 2 x 2	2 x 2 x 2 x 3	2 x 2 x 2 x 3	2 x 2 x 2
Main Effects	Group, Domain, Feature	Group, Domain, Feature, Load	Group, Domain, Feature, Day	Group, Domain, Feature
Interaction Effects	Group x Domain x Feature, Group × Domain, Group × Feature, Domain × Feature	Group × Domain × Feature × Load, Group × Domain × Feature, Group × Domain × Load, Group × Feature × Load, Domain × Feature × Load, Group × Domain, Group × Feature, Group × Load, Domain × Feature, Domain × Load, Feature × Load	Group × Domain × Feature × Day, Group × Domain × Feature, Group × Domain × Day, Group × Feature × Day, Domain × Feature × Day, Group × Domain, Group × Feature, Group × Day, Domain × Feature, Domain × Day, Feature × Day	Group x Domain x Feature, Group × Domain, Group × Feature, Domain × Feature
Random Effect Intercepts	Participant, Trial, Stimulus, Hue, Theta	Participant, Trial, Stimulus, Hue, Theta	Participant, Trial, Stimulus, Hue, Theta, Repetition across Days	Participant, Trial, Stimulus, Hue, Theta
Random Effect Slopes	Participants × Feature, Stimulus x Feature	Participants × Feature, Participants × Load, Stimulus x Feature	Participants × Feature, Participants × Day, Stimulus x Feature, Stimulus x Day	Participants × Feature, Stimulus x Feature
Primary Effects of Interest	Domain x Feature	Domain x Feature x Load	Domain x Feature	Domain x Feature

Note. Table summarizing the main effects, interaction effects, random effect intercepts, random effect slopes, and primary effects of interest for the linear mixed models computed for the three tasks: visual perceptual task, short-term memory task, long-term memory task (study phase), and long-term memory task (testing phase).

follow a systematic backward selection approach. Initially, we will start with the maximal model (see Table 2) for each task and progressively simplify the models by removing the random effects with the smallest variance in the instance where a model fails to converge. For all analyses outlined below, any significant interactions will be followed by post-hoc analyses to determine the source of the interaction and to clarify whether the predictions were supported.

In all tasks, we predict a significant interaction between domain and feature. This two-way interaction between domain and feature is the primary effect of interest for the visual perceptual task and the study phase, and the testing phase of the long-term memory task (which is the key phase of interest in this task). In these analyses, we predict that participants will perform relatively better in the feature that is congruent with their synesthesia or expertise. Specifically, grapheme-color synesthetes and color experts are expected to perform relatively better in the color feature, while sequence-space synesthetes and spatial experts are expected to perform relatively better in the spatial feature. During the study phase of the visual long-term memory task, we anticipate seeing performance improvements in the feature congruent with participants' synesthesia or expertise on each day. In the visual short-term memory task, the primary effect of interest is the interaction between domain, feature, and load, where we predict the above pattern of results across all loads. Specifically, we predict that participants will perform relatively better in in the feature that is congruent with their synesthesia/expertise in all loads. We predict that these effects will be more pronounced in loads one and three. For load five, although we expect relatively better performance from participants whose domain and feature conditions are congruent, we predict that performance will asymptote for all participants regardless of domain or feature condition (Zhang & Luck, 2008).

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Deleted: Finally, for the long-term memory task (study phase), the primary effect of interest is the interaction between domain, feature, and day.

To investigate our second hypothesis, where we expect participants' performance (regardless of group or domain) in the color feature conditions to correlate across the different versions of the task, and participants’ performance in the spatial feature conditions to correlate across the different versions of the task, we'll construct a Pearson’s correlation matrix. In this matrix, we'll correlate performance measures from both the color and spatial feature conditions across the visual perceptual, visual short-term memory, and visual long-term memory tasks. We hypothesize that accuracy in the three tasks will exhibit positive correlations within their respective feature conditions. We also anticipate that the inter-task correlation coefficients regarding the color (spatial) feature condition will significantly differ from those of the spatial (color) feature condition. To investigate this, we will conduct a significance test on the correlation coefficients across the three tasks in the two conditions using the *cocor* package (Diedenhofen & Musch, 2015; version 1.1.4) in R.

To investigate our third and final hypothesis, where we predict that grapheme-color synesthetes and color experts will share a common cognitive profile and perform similarly to each other, while sequence-space synesthetes and spatial experts will likewise share a common cognitive profile and similar performance, we will conduct two cluster analyses. Through these analyses, we aim to identify whether individuals categorized as either color experts or grapheme-color synesthetes exhibit greater similarity in their performance, potentially forming a clustered cognitive profile referred to as a "color profile". Additionally, we aim to determine if spatial experts and sequence-space synesthetes similarly cluster together, signifying a shared cognitive profile called a "spatial profile". To analyze this, the first cluster analysis will use *k-means* clustering using the *flexclust* package (Leisch, 2006; version 1.4.1) in R. For this, we will only use participants' performance metrics from the visual perceptual, visual short-term memory and visual long-term memory tasks, specifically the measure of absolute angular deviation for both, the spatial and color feature conditions. To categorize participants based on their cognitive profile, those categorized as grapheme-color synesthetes or color experts will be coded as category 1, while those categorized as sequence-space synesthetes, or spatial experts will be coded as category 2. We will then calculate the Euclidean distance between data points. The appropriate number of clusters will then be determined using the *NbClust* package (Charrad et al., 2014; version 3.0.1) in R. Finally, we will use the *flexclust* package to quantify the agreement between participants' cognitive profile and their assigned cluster using the adjusted Rand index. This index provides a measure of the agreement between two partitions, adjusted for chance, and ranges from -1 (no agreement) to 1 (perfect agreement). The above cluster analysis will then be repeated, but this time we will also integrate participants' responses on the Sussex Cognitive Styles Questionnaire in addition to their performance on the spatial and color feature conditions. These questionnaire responses will aid in distinguishing between dorsal and ventral visual processing among participants. By including both task-related performance measures and questionnaire responses, we aim to develop a comprehensive understanding of participants' cognitive profiles. This approach allows us to explore not only their performance in the tasks but also their cognitive processing styles.

All analyses detailed above will be repeated using a more conservative approach. In this approach, only participants with complete datasets will be included. This will help us determine if the results remain consistent compared to when participants with less complete datasets (but more than 50% of the data) are included.

A priori power calculation

The power calculation for this study was conducted in two steps. First, we simulated an artificial dataset from the pilot data collected from the three tasks through bootstrapping. Second, for each task, we built a model from the artificial dataset and used the effect sizes from this model to determine the required sample size.

For each of the three tasks, we simulated a difference with a Cohen's *d* of 0.4 for domain between the spatial feature condition and the color feature condition (see Brysbaert, 2019 for the smallest effect size of interest in psychological research) for domain between the spatial feature condition and the color feature condition. Figure 4 presents the means and standard deviations from the pilot data, along with the simulated means and standard deviations derived for each task.

To determine the sample size, we conducted a power analysis using the *mixedpower* package (Kumle et al., 2021; version 0.1.0) in R, by simulating data on all three tasks. The power analysis detailed below includes the number of participants required for both, 90% power (at an alpha level of .02) and 80% power (at an alpha level of .05).

Artificial dataset simulation

To calculate the sample size for this study, we first generated an artificial dataset by bootstrapping the means and standard deviations from the pilot study (see Figure 4). This method was applied to each of the three tasks: the visual perceptual task, the visual short-term memory task, and the visual long-term memory task. The pilot data were collected from non-synesthetic controls recruited from the student participant pool at UniDistance Suisse.

For each task, an artificial dataset was simulated for 200 participants. An equal number of participants were characterized as grapheme-color synesthetes (n = 50), color experts (n = 50), sequence-space synesthetes (n = 50), and spatial experts (n = 50). Crucially, grapheme-color synesthetes and color experts were considered controls in the spatial feature condition and test groups in the color feature condition. Conversely, sequence-space synesthetes and spatial experts were considered controls in the color feature condition and test groups in the spatial feature condition. In their control conditions, participants are expected to perform similarly to our pilot participants, who were neither synesthetes nor experts in either domain. Based on this assumption, normally distributed data was generated using the mean and standard deviation of performance from the pilot data.

In both test conditions, we expect participants to perform relatively better than our pilot participants. Specifically, we assume that sequence-space synesthetes and spatial experts will perform relatively better in the spatial feature condition than in the color feature condition. Conversely, we assume that grapheme-color synesthetes and color experts will perform relatively better in the color feature condition than in the spatial feature condition. Based on these assumptions, we generated normally distributed data by simulating a difference in the mean from the pilot data with a Cohen's *d* of 0.6. This choice of a Cohen's *d* of 0.6 results in a difference of the difference, with a Cohen's *d* of 0.4, which represents the interaction of interest in each task. The difference of the difference refers to the interaction effect, which indicates the relatively better performance of synesthetes and experts in the feature that is congruent with their synesthesia/expertise compared to their performance in the feature that is incongruent with their synesthesia/expertise.

Artificial data for the visual perceptual task was generated using the method described above for the color and spatial features. For the visual short-term memory task, datasets for both the color and spatial feature conditions were simulated with a Cohen's *d* effect size of 0.4 for all load conditions using the assumptions described above. Similarly, for the visual long-term memory task, datasets with a Cohen's *d* effect size of 0.4 were simulated for both feature conditions across all days.

A priori power analysis

For each of the three tasks, the simulated artificial dataset was then used to construct the corresponding linear mixed models as outlined in the analysis section (see Table 2). Subsequently, the beta estimates derived from the models were employed in a power simulation comprising 500 iterations, varying the number of participants in increments of 20, 30, 40, 50, and 60. The primary focus was on achieving at least 90% power for the interactions of interest; however, we will also report how many participants we will need to achieve at least 80% power in case we cannot recruit our ideal number of participants.

Deleted: To determine the sample size, we conducted a power analysis using the *mixedpower* package (Kumle et al., 2021; version 0.1.0) in R, by simulating data on all three tasks. The power analysis detailed below includes the number of participants required for both, 90% power (at an alpha level of .02) and 80% power (at an alpha level of .05). For each of the three tasks, we will apply a Cohen's *d* of 0.6 to simulate the difference between participants in the color domain and those in the spatial domain for each feature condition (color and spatial). This enables us to observe a difference in domain between the spatial feature condition and the color feature condition, with a Cohen's *d* of 0.4 (see Brysbaert, 2019 for the smallest effect size of interest in psychological research). This represents the difference of a difference, resulting in the interaction of interest. Table 3 presents the means and standard deviations from the pilot data, along with the simulated means and standard deviations derived for each task.In the visual perceptual task, simulated data were generated based on 200 simulated participants. An equal number of participants were characterized as grapheme-color synesthetes (*n* = 50), color experts (*n* = 50), sequence-space synesthetes (*n* = 50), and spatial experts (*n* = 50). To simulate data for the color and spatial feature conditions, we employed the mean and standard deviation derived from the pilot data, where for participants who were not categorized as sequence-space synesthetes or spatial experts, we generated normally distributed data using the mean and standard deviation of performance on the spatial feature from the pilot data. Conversely, for participants who were categorized as sequence-space synesthetes or spatial experts, we generated normally distributed data using a Cohen's *d* of 0.6 (note that this leads to a difference with a Cohen's *d* of 0.4 for the interaction of interest) for the difference in the mean absolute angular deviation score, while maintaining a constant standard deviation of 2.77 degrees.

For the visual perceptual task, the power analysis indicated that employing 20 participants in each group (i.e., 80 participants in total) would ensure 97.4% power to detect a Cohen's *d* effect size of 0.4 for the interaction between the domain and feature conditions at an alpha level of .02. This number of participants would also ensure a power of 99.4% at an alpha level of .05. For the visual short-term memory task, the power analysis found that 20 participants in each group (i.e., 80 participants in total) would ensure at least 96.6% power to detect the interaction of interest (between domain, load, and feature) at a Cohen's *d* effect size of 0.4 at an alpha level of .02. With 20 participants in each group, we would also achieve at least 98.6% power at an alpha level of .05. Finally, for the visual long-term memory task, the power analysis indicated that 40 participants would be required in each group (i.e., 160 participants in total) to achieve at least 97% power to detect a Cohen's *d* effect size of 0.4 for the interaction between domain, day, and feature at an alpha level of .02. With 20 participants in each group, we would ensure at least 85% power to detect the interaction of interest at an alpha level of .05.

Deleted: A similar approach was used for the color feature condition, where for participants categorized as grapheme-color synesthetes or color experts, we generated normally distributed data using the mean and standard deviation of performance on the color feature from the pilot data. Conversely, for participants categorized as grapheme-color synesthetes or color experts, we generated normally distributed data using a Cohen's *d* of 0.6 for the difference in the mean absolute angular deviation score, while maintaining a standard deviation of 6.96 degrees.

Figure 4

	Visual Perceptual Task	Visual Short-Term Memory Task (Load One)	Visual Short-Term Memory Task (Load Three)	Visual Short-Term Memory Task (Load Five)	Visual Long-Term Memory Task (Day one, Repetition one)	Visual Long-Term Memory Task (Day one, Repetition two)	Visual Long-Term Memory Task (Day two, Repetition one)	Visual Long-Term Memory Task (Day two, Repetition two)	Visual Long-Term Memory Task (Day three, Repetition one)	Visual Long-Term Memory Task (Day three, Repetition two)
Pilot Mean (SD) Spatial Feature (degrees)	2.65 (2.77)	6.91 (9.83)	22.50 (34.05)	50.11 (51.27)	35.97 (45.95)	20.15 (30.38)	23.03 (33.87)	13.05 (17.56)	18.20 (30.48)	11.80 (18.23)
Pilot Mean (SD)Color Feature (degrees)	4.84 (6.96)	17.80 (25.07)	34.18 (40.14)	62.76 (52.45)	55.10 (50.13)	36.31 (42.12)	36.24 (41.64)	29.08 (36.31)	28.53 (35.71)	22.21 (28.29)
Mean (SD) Spatial Feature (degrees) in Color Domain	3.54 (2.17)	10.90 (7.25)	37.55 (24.99)	63.44 (38.83)	52.95 (34.05)	33.03 (22.21)	36.84 (24.11)	19.71 (13.16)	32.00 (21.58)	19.62 (13.30)
Control Mean (SD) Color Feature (degrees) in Spatial Domain	7.62 (5.06)	28.53 (18.62)	47.85 (30.86)	72.43 (41.03)	67.22 (40.02)	50.69 (32.17)	50.91 (32.27)	42.25 (27.58)	42.38 (27.35)	32.52 (20.97)
Mean (SD) Spatial Feature (degrees) in Spatial Domain	2.63 (1.84)	8.18 (6.00)	28.11 (21.16)	48.59 (33.82)	39.82 (28.77)	24.74 (18.20)	27.35 (21.00)	15.07 (11.30)	24.25 (18.21)	14.82 (11.01)
Mean (SD) Color Feature (degrees) in Color Domain	5.78 (4.39)	21.23 (15.60)	35.36 (25.71)	54.90 (36.77)	50.30 (34.43)	37.62 (27.09)	37.89 (26.89)	31.72 (22.85)	31.24 (23.00)	24.41 (17.88)

Note. Figure of a table presenting the means and standard deviations for all tasks. The rows display the means and standard deviations from the pilot data for both color and spatial features. Additionally, the table includes the simulated means and standard deviations for the spatial and color features within the simulated groups in the spatial and color domain.

Deleted: **Using the simulated data, we constructed the same linear mixed model for the visual perceptual task as outlined in the analysis (see Table 2). Subsequently, the beta estimates derived from this model were employed in a power simulation comprising 500 runs, varying the number of participants in increments of 20, 30, 40, 50, and 60. The primary focus was on achieving at least 90% power the interaction between domain and feature as this represents the primary effect of interest. The power simulation indicated that employing an estimated 20 participants in each group would ensure 97.4% power to detect a Cohen's *d* effect size of 0.4 for the interaction between domain and feature conditions at an alpha level of .02. With 20 participants in each group, we would also ensure a power of 99.4% at an alpha level of .05.**

Table 3

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where We then performed a power simulation for the visual short-term memory task following the same method with 200 simulated participants. In the spatial feature condition, for all load conditions, we simulated a dataset where participants categorized as sequence-space synesthetes or spatial experts exhibited a lower absolute angular deviation than those who were not, with a Cohen's d effect size of 0.6. Likewise, in the color feature condition, for all load conditions, participants categorized as either grapheme-color synesthetes or color experts displayed a lower absolute angular deviation than those who were not with a Cohen's d The power simulation found that for this task, to achieve at least 90% power for the interaction between domain, load, and feature, an estimated total of 20 participants would need to be recruited to ensure at least 96.6% power to detect the interaction of interest at a Cohen's *d* effect size of 0.4 at an alpha level of .02. With 20 participants, we would also ensure at least 98.6% power to detect the interaction of interest at a Cohen's *d* effect size of 0.4 at an alpha level of .05.

The power analysis for the study phase of the visual long-term memory task was conducted in the same way as for the previous tasks with 200 simulated participants. The power simulation with 500 runs for this model found that an estimated 40 participants would be required to achieve at least 97% to detect a Cohen's *d* effect size of 0.4 for the interaction between domain, day, and feature at an alpha level of .02. With 20 participants we would also ensure at least 85% power to detect a Cohen's *d* effect size of 0.4 for the interaction of interest at an alpha level of .05.

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Supplementary materials

Supplementary Table 1

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**
Do synesthetes and experts demonstrate enhanced performance in visual perception and visual memory for their congruent feature?	We predict a double dissociation between Domain and Feature where grapheme-color synesthetes and color experts will perform better on the color feature compared to the spatial feature, while sequence-space synesthetes and spatial experts will perform better on the spatial feature than on the color feature.	We aim to collect at least 160 participants in total, with a minimum of 40 participants in each of the four groups: grapheme-color synesthesia, color experts, sequence-space synesthesia, and spatial experts.	We will use a 2 x 2 x 2 Linear Mixed Model with the between-subjects factors Group (Synesthete vs. Expert) and Domain (Color vs. Spatial), and the within-subjects factor Feature (Color vs. Spatial). In the visual short-term memory task, this model will be extended to include the within-subjects factor Load (one, three, and five). In the visual long-term memory task (study phase), the model will be extended to include the within-subjects	We powered our experiment for a Cohen's *d* of 0.4 to observe a difference in domain between the spatial feature condition and the color feature condition, in line with Brysbaert's (2019) review on the smallest effect size of interest in psychological research.	If we find an interaction between Domain and Feature, where synesthetes and experts demonstrate enhanced performance in visual perception and memory on their congruent feature, this would lend support to the enhanced processing account, where participants in the color domain will show enhanced performance in the color feature but not in the spatial feature, and vice versa for participants in the spatial domain.	No support for the enhanced processing account, which posits a distinction between the ventral and dorsal visual pathways and suggests that memory and perception are closely related within their respective pathways.

Deleted: This represents a difference of differences, resulting in the interaction of interest.

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**
			factor Day (one, two, and three).			
Does participants' perception of color features significantly predict their memory for color features, and does their perception of spatial features significantly predict their memory for spatial features, irrespective of group and across all tasks?	We predict participants' performance (regardless of group or domain) in the color feature conditions to correlate across the different versions of the task, and participants' performance in the spatial feature conditions to correlate across different versions of the task. We also predict that the correlation coefficients between tasks regarding the color (spatial) feature condition will significantly differ from those of the	Same as above.	We will conduct Pearsons correlations between performance measures from both color and spatial feature conditions across the visual perceptual, visual short-term memory, and visual long-term memory tasks. To investigate the difference in the inter-task correlation coefficients, we will conduct a significance test on the correlation coefficients across the three tasks in the two feature conditions.	Same as above.	A positive correlation between performance measures for color and spatial feature conditions would suggest a close relationship between perception and memory. Additionally, conducting a significance test on the correlation coefficients across the tasks in the two feature conditions would help elucidate the differences between the ventral and dorsal visual pathways.	Same as above.

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
	spatial (color) feature condition.					
Do grapheme-color synesthetes and color experts exhibit a similar cognitive profile, while sequence-space synesthetes and spatial experts exhibit a similar cognitive profile?	We predict that grapheme-color synesthetes and color experts will share a similar cognitive profile, where they will perform similarly to each other. Likewise, sequence-space synesthetes and spatial experts will share a similar cognitive profile where they will perform similarly to each other.	Same as above.	We will conduct two k-means cluster analyses. For the first cluster analysis, we will use participants' performance metrics from the visual perceptual, visual short-term memory, and visual long-term memory tasks, specifically the measure of absolute angular deviation for both the spatial and color feature conditions. For the second cluster analysis, we will use participants' performance metrics in the three tasks across the two	Same as above.	If the clusters align with the hypothesized groups (e.g., grapheme-color synesthetes and color experts forming one cluster, sequence-space synesthetes and spatial experts forming another), it would suggest that these groups share similar cognitive profiles. This alignment would support the notion that synesthesia and expertise in specific domains (color or spatial) lead to similar performance patterns in visual perception and memory tasks.	If the clusters do not align with the hypothesized groups, it would indicate that the cognitive profiles of synesthetes and experts are more heterogeneous than expected. This outcome could suggest that factors other than synesthesia and domain expertise contribute to the observed performance patterns in visual perception and memory tasks.

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
			feature conditions, as well as their responses on the Sussex Cognitive Styles Questionnaire.			

Note. Table depicting the analysis plan for this study. All analyses will be two-tailed.

Split-half reliability

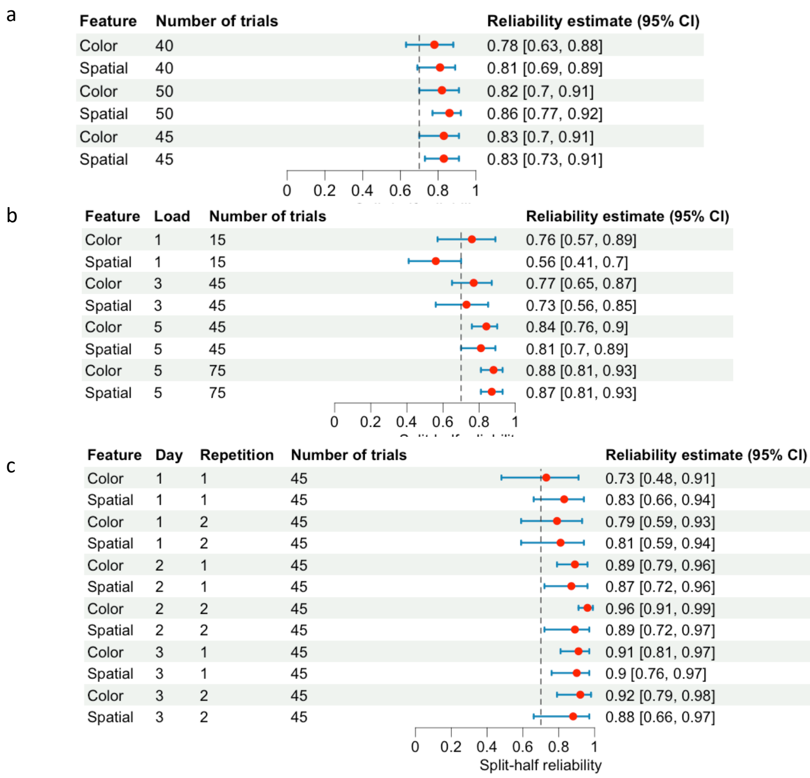
To determine the number of trials required for a reliable estimation of our data in each task, we conducted a split-half reliability assessment on our pilot data using the *splithalf* package in R (Parsons, 2021, version 0.8.2). Our pilot data consisted of non-synesthetic controls from the student pool at UniDistance Suisse. This procedure involves iteratively splitting the data in half (5000 iterations in this case) and computing the outcome scores for each half. Subsequently, the Spearman-Brown correlation coefficient between each pair of halves is calculated for each iteration and the average correlation is determined as the final reliability estimate. A Spearman-Brown correlation coefficient of r_{SB} = .7 or higher is generally considered indicative of good reliability.

For the visual perceptual task, we conducted a split-half reliability estimate on pilot data consisting of 50 trials and 37 participants (see Supplementary Figure 1a). The split-half reliability analysis was conducted for both color and spatial feature conditions with all trials (i.e., 50 trials), the first 45 trials, and the first 40 trials. Since the gain in reliability from 45 trials to 50 trials was marginal, we decided to proceed with 45 trials for the visual perceptual task.

For the visual short-term memory task, we conducted a split-half reliability estimate on pilot data consisting of 36 participants (see Supplementary Figure 1b). A split-half reliability estimate was calculated for each of the three loads for both color and spatial feature conditions. In the pilot, load one consisted of 15 trials and 15 stimuli (as each trial presented one stimulus). In this load, the reliability for the spatial feature was low (r_{SB} = .57). For load three, we found that the reliability estimates with 15 trials (with 45 stimuli in total) for both color and spatial feature conditions were above .7. Similarly, for load five, we found that the reliability estimates with 15 trials (with 75 stimuli in total) for both color and spatial feature conditions were above .8. Since the load one condition included only 15 trials (with 15 stimuli in total), we applied the Spearman-Brown equation as described by Brysbaert (2019, page 21) to determine how many trials would be needed to achieve a reliability estimate of over .7. Using this equation, we found that 27 trials (i.e., 27 stimuli in total) would yield an r_{SB} of .7, while 45 trials (i.e., 45 stimuli in total) would yield an r_{SB} of .8. Given these estimates, we decided to increase the number of trials for load one to 45 trials (i.e., 45 stimuli in total), keep the number of trials for load three the same (i.e., 15 trials with 45 stimuli in total), and decrease the number of trials for load five to 9 trials (i.e., 45 stimuli in total).

We conducted the pilot study for the visual long-term memory task with 45 trials. Split-half reliability estimates were calculated for all days and both repetitions for both color and spatial features (see Supplementary Figure 1c). All reliability estimates for this task were over 0.7. Therefore, to maintain consistency between tasks, we decided to use 45 images for the visual long-term memory task, with participants completing a total of 45 trials split across three blocks.

Supplementary Figure 1



Note. Figure illustrating split-half reliability estimates with 95% confidence intervals. Split-half reliability is depicted on the x-axis, with the dashed line indicating r_{SB} = .7. "Feature" indicates whether participants adjusted for color or spatial features, while "Number of trials" denotes the trials used for reliability estimates. Panel a) shows reliability estimates for the visual perceptual task with 50, 45, and 40 trials. Panel b) displays reliability estimates for the visual short-term memory task with 15 trials in load one, 45 trials in load 3, and 45 and 75 trials in load 5. Panel c) presents reliability estimates for the visual long-term memory task with 45 trials across all days and repetitions.