Exploring the relationship between grapheme colour-picking consistency and mental imagery

Mary Jane Spiller[1], Lee Harkry[1], Fintan McCullagh[1], Volker Thoma[1] and Clare Jonas[1]

1 School of Psychology, University of East London, London E14 4LZ

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Summary

Previous research has indicated a potential link between mental imagery and synaesthesia. However, these findings are mainly based on imagery self-report measures and recruitment of self-selected synaesthetes. To avoid issues of self-selection and demand effects we recruited participants from the general population, rather than synaesthetes specifically, and used colour-picking consistency tests for letters and numbers to assess a "synaesthete-like" experience. Mental imagery ability and mental rotation ability were assessed using both self-report measures and behavioural assessments. Consistency in colour-picking for letters (but not numbers) was predicted by performance on the visual mental imagery task, but not by a mental rotation task or self-report measures. Using the consistency score as a proxy measure of grapheme-colour synaesthesia, we provide more evidence for the suggestion that synaesthetic experience is associated with enhanced mental imagery, even when participants are naïve to the research topic.

[1] *Author for correspondence (m.j.spiller@uel.ac.uk).
†Present address: School of Psychology, University of East London, London E14 4LZ

Introduction

Having synaesthesia is not the only thing that separates synaesthetes from the rest of the population. Over the last decade, synaesthesia researchers have begun painting a picture of synaesthesia in relation to various aspects of sensation (1), perception (2), cognition (e.g. memory 3), personality (4; 5) and more recently physical and mental health (e.g. 6- 9). By exploring these relationships between synaesthesia and other psychological features, we can more fully comprehend the developmental, behavioural, neurological and genetic aspects of the phenomenon. These relationships are then used to build subsequent ideas and research questions concerning synaesthesia and individual differences. However, there are often important limitations to these studies such as recruitment methods and samples sizes (e.g. 10), restricting the strength of conclusions that be drawn. The current paper focuses on the possible relationship between synaesthesia and mental imagery (for a discussion see 11). We will first consider why mental imagery might be expected to have a relationship with synaesthesia, then look at the studies to date that have explored this area, with a focus on their limitations. We then present a study that takes a novel approach by exploring the possible relationship between grapheme colour-picking consistency and mental imagery abilities in the general population.

Like synaesthesia, mental imagery can be experienced across all sensory modalities. Mental images can be thought of as "representations and the accompanying experience of sensory information without a direct external stimulus" (12, p.590), and similarly a synaesthete has the experience of perceptual information such as colour or taste when presented with their synaesthetic "inducer" (for example, a grapheme). This synaesthetic "concurrent" is experienced in the absence of the usual direct external stimulus. Brain activity recorded during some mental imagery tasks shows accompanying activity in the primary sensory areas of the brain (13) and likewise, some synaesthesia studies have reported increased activity in the primary sensory areas of the brain relating to the modality of the concurrent (14-15). Importantly, both mental imagery studies and synaesthesia studies are increasingly showing the role of a broad network of activity across the brain during the experience of the concurrent or mental image (16-18). People vary in the extent to which they can generate or make use of mental imagery (19), with some reporting no imagery at all ("aphantasia" 20). While most people do not experience synaesthesia (only 1-2.5% of population experience synaesthesia grapheme colour synaesthesia, 21-22), almost everybody makes use of crossmodal associations such as non-consciously associating high pitched sounds with lighter colours and low pitched sounds with darker colours (see 23 for debate about similarities between synaesthesia and crossmodal associations). Crucially, mental images generally require effort to generate and use, whereas synaesthetes report that their synaesthetic concurrents occur with little if any effort and yet can be detrimental to task performance (e.g. 24). Further similarities between synaesthesia and mental imagery can be found when considering traits typically associated with enhanced imagery and traits associated with synaesthesia, such as positive schizotypy (e.g. 25-27 for further consideration) and fantasizing (e.g. 4, 28).

It can therefore be seen that mental imagery and synaesthesia have many similarities, but importantly some key differences. Accordingly, in order to understand synaesthesia, it is important to explore its relationship with mental imagery. If enhanced mental imagery is a trait associated with some or all forms of synaesthesia, then this has wider implications for study designs when exploring other aspects of synaesthesia. Furthermore, the question of whether enhanced imagery is restricted to the modalities in which an individual experiences synaesthesia, or has a broader reach across all imagery modalities, has implications for the questions regarding the impact of synaesthesia on cognition more generally. For example, Rouw et al (17) have suggested the idea of a 'synaesthetic constitution' in relation to the finding that function and structural brain differences are not only found in the sensory areas of the brain involved with the synaesthetic concurrent and inducer, but can be seen across all sensory areas.

Whilst one study has looked at whether a visual mental image of a grapheme is sufficient to induce grapheme-colour synaesthesia (29), others have focused on the question of whether synaesthetes have enhanced mental imagery. Barnett and Newell (30) found that (mostly grapheme-colour) synaesthetes report more vivid visual imagery compared to non-synaesthetes (relatives without synaesthesia and control participants) using the Vividness of Vivid Imagery Quota (VVIQ, 31), and this finding has since been replicated (for example see 27). Price (32) found that compared to non-synaesthetes, sequence-space synaesthetes (experiencing sequences such as time, number, dates in spatial locations) reported greater use of visual mental imagery than non-synaesthetes with the Spontaneous Use of Imagery Scale (SUIS, 33) and more vivid mental imagery on the object but not spatial subscale of the Object-Spatial Imagery Questionnaire (OSIQ, 34). Havlik et al (35) also reported higher scores on the SUIS for sequence space synaesthetes compared to non-synaesthetes.

Other studies have found similar results using different self-report measures of visual mental imagery. Chun and Hupé (10) found that (mostly grapheme-colour) synaesthetes reported greater intensity and usage of mental imagery with the French Questionnaire on Mental Imagery-51 (FQMI-51). On the Sussex Cognitive Styles Questionnaire (SCSQ, 36), grapheme-colour and sequence-space synaesthetes scored higher on the Imagery Ability subscale than non-synaesthetes (this has since been replicated for sequence-space synaesthetes (37), but grapheme-colour synaesthetes were not tested).

The studies mentioned so far, showing a reliable relationship between mental imagery and synaesthesia, have only used visual-spatial forms of synaesthesia using self-report measures of visual-spatial imagery. In Spiller et al. (38), we expanded this by comparing imagery self-reports of synaesthetes to non-synaesthetes across a wide range of imagery modalities and with a range of synaesthesia sub-groups. We found that reports of enhanced imagery are not limited to visual-spatial imagery or visual-spatial forms of synaesthesia, with reports of enhanced auditory, olfactory, taste, touch and movement imagery in synaesthetes with both visual and non-visual forms of synaesthesia, when compared to non-synaesthetes. Interestingly, we found enhanced imagery reports in specific modalities were associated with both the inducer and the concurrent modality. Furthermore, as the number of forms of synaesthesia reported by an individual increased, so did the vividness of mental imagery reported, across all modalities.

Taken together, the self-report studies generally find that synaesthetes report greater vividness and more usage of mental imagery than non-synaesthetes, which is not limited to particular forms of imagery or variants of synaesthesia (but see 10 for comments about effect sizes and gender as a possible confounding variable). Of course, it is essential to keep in mind that self-report measures are not direct measures of imagery ability (e.g. see 39 for VVIQ and socially desirable responding but also see 40 for observable neural correlates of high and low scores on the VVIQ).

It is not clear whether or how reports of enhanced imagery use or imagery vividness are related to the behavioural advantage seen in synaesthetes carrying out mental imagery tasks. Some studies have found that sequence-space synaesthetes perform better on measures of mental rotation than non-synaesthetes (35, 41- 42; but see 43), and individual differences relating to synaesthetic experience seem to be a determining factor relating to this advantage (35). Only one study to date has reported grapheme-colour synaesthetes showing a behavioural advantage on a mental imagery task; Spiller and Jansari (29) found that grapheme-colour synaesthetes were significantly faster than non-synaesthetes at a visual mental imagery task that involved generating an image of a letter against a colour background and making a size-based decision about the image. This advantage was even found in the trials when the background colour hampered their performance. Although that study had not been designed to explore differences in mental imagery ability it is suggestive of a possible behavioural advantage in mental imagery abilities in individuals with synaesthesia, at least when it comes to grapheme-colour synaesthetes performing tasks involving mental images of graphemes.

To summarise, there is a growing body of evidence that suggests synaesthesia may be associated with enhanced mental imagery, as measured by self-reports of imagery use, vividness and/or ability. There is limited evidence to suggest this may translate to a behavioural advantage on some mental rotation or mental imagery tasks. To date, we do not have a study that has combined self-report measures with those of both mental rotation and mental imagery task performance (within the same sample). Another limitation of previous studies (and a common problem with synaesthesia research), is the method used for recruiting participants (see 10 for discussion and 44 for a recent study using a double-blind method) and the impact this might have on the findings. Synaesthete participants are typically recruited from a pre-existing database that researchers have developed over years of conducting synaesthesia research, where synaesthetes have completed synaesthesia screening tools and consistency measures. They are therefore aware that they are being recruited for a study due to the presence of their synaesthesia, leading to potential bias in their responses or behaviour. In contrast, the comparison non-synaesthete 'control' group is recruited from university populations or acquaintances of the researcher and may not have the same motivations for taking part in the research. Furthermore this method also raises the possibility of excluding participants from the sample who are unaware that they have synaesthesia, resulting in an unrepresentative sample of synaesthetes. Indeed, Simner (11) has suggested that results showing synaesthetes reporting enhanced imagery may be driven by this recruitment bias, as those synaesthetes with vivid imagery are more likely to be aware of their synaesthesia, and so in turn, more likely to self-refer to researchers.

The current study therefore was designed to explore the relationship between grapheme colour-picking consistency and mental imagery abilities. Instead of recruiting synaesthete and non-synaesthete participants, we recruited from the general population, and did not specifically mention synaesthesia until the very end of the study. The expectation is that this will eliminate, or at least reduce, any demand characteristics arising from awareness of our focus on synaesthesia (see 45). It will also allow the possible recruitment of individuals who are unaware of having synaesthesia, providing a fuller picture of the relationship between mental imagery and synaesthesia.

As a measure of synaesthete-like behaviour, participants completed a grapheme colour-picking task to record their colour-picking consistency (based on 46). In this task, participants were presented with a series of letters and numbers, each time selecting a colour that they associate with the grapheme. A measurement of consistency across multiple viewing of the graphemes then provides us with a proxy measure of synaesthesia, as people who are more consistent in their colour choices are more likely to be synaesthetes. Since synaesthesia seems to be associated with enhanced mental imagery, we would expect greater consistency in colour picking to be associated with reports of enhanced imagery and better performance on mental imagery tests.

Ward et al (37) similarly looked at non-synaesthetes' performance on a consistency measure for sequence-space synaesthesia, in addition to their responses to a questionnaire about sequence-space synaesthesia experiences. Interestingly, they found that non-synaesthetes who passed the consistency test but did not resemble a synaesthete with their questionnaire responses *did not* report enhanced mental imagery, whereas those who failed the consistency test but did resemble a synaesthete in their sequence-space questionnaire responses *did* report enhanced imagery. Based on this, we might predict that synaesthesia-like responses on our colour picking task would not relate to enhanced imagery ability. However, Ward et al were assessing sequence-space synaesthesia and performed group comparisons, whereas we are focusing on grapheme-colour associations and using continuous measures. Based on the body of literature reviewed earlier, we predicted that we would find a relationship between colour-picking consistency and the measures of mental imagery ability chosen for this study.

We chose four different measures of mental imagery, comprising two self-report measures and two behavioural tasks. The self-report measures related to visual mental imagery vividness (the VVIQ) and visual mental imagery use (the SUIS). These have both been used frequently in the synaesthesia and mental imagery literature, and several studies (as outlined already) show that synaesthetes score differently to non-synaesthetes on these measures. We therefore predicted a relationship between scores on these measures and our colour-picking consistency measure.

Having behavioural tasks that tap different aspects of mental imagery was an important element of the design, as mental imagery is not a unitary construct (19). Consequently, we selected an imagery task related to object imagery and another related to spatial imagery. To test ability to generate and inspect a visual mental image, participants completed the 'Animal Tails Task' (47). In this task participants are asked to visualise a series of animals and make a size-based decision about the animal's tail (animals chosen for the task are not characteristically associated with their tail). Determining the size or shape of animal features has been shown to involve the invocation and inspection of mental images as these facts are typically only encoded visually (48), and the task has previously been used to explore the relationship between visual imagery and visual perception (49, 50).

Furthermore, participants completed a mental rotation task (Mental Rotations Task, MRT-A, 51) that assesses ability to mentally rotate 3D abstract blocks. The studies to date that have explored mental rotation abilities of synaesthetes have focused on sequence-space synaesthesia, so it is not known whether grapheme-colour synaesthesia would be associated with an enhanced ability to perform mental rotation. We also included proxy measures of numeracy and IQ to control for possible confounding factors.

In sum, we aimed to test whether scores on a grapheme colour-picking consistency task (as a proxy measure of synaesthesia that reduces the issue of response bias) could be predicted by performance on both behavioural mental imagery and mental rotation tasks and scores on mental imagery self-report measures.

Method

Participants

We recruited 75 participants (naïve to the study's aims) from the university campus and acquaintances of the researchers. Due to the nature of the colour-picking consistency test we wanted to ensure that we did not include participants who may have misunderstood the task instructions and had selected the same colour for every trial. Consequently, upon inspection of the colours chosen, we excluded five of the participants from the data analysis (although note that results remain the same overall when N = 75 and the complete data set is available in Supplementary Materials). The remaining 70 participants (42 females, 28 males) were aged between 20 and 48 (M = 31.67, SD = 6.99). Participants had normal or corrected-to-normal eyesight, and did not experience colour-blindness or any clinical neurological conditions. Most participants were educated to at least starting university level (N = 61, 87%), and right handed (N = 61, 87%). Participants were given the opportunity for entry into a prize draw for a £100 shopping voucher.

At the final stage of the study participants were asked about their knowledge and experience of synaesthesia (see Materials and Procedure). Just over half of the participants indicated prior knowledge of synaesthesia (N = 37, 53%), and eight participants (11%) reported being a synaesthete. Interestingly, 28 participants (40%) went on to answer positively about having at least 1 form of synaesthesia (15 reported 1 form, 7 reported 2 forms, 4 reported 3 forms and 2 reported 5 forms). We do not have any measure of consistency to corroborate these reports, but of relevance to this study, 11 participants (16%) reported that they associated numbers or letters with colours (see Results for how this relates to Colour-Picking Consistency performance).

Materials and Procedure

Participants completed the study individually either in a testing room on campus (N=35) or in quiet locations off-campus (N=35) (note that performance on measures did not differ significantly between different locations). Participants were told that the study consisted of both paper and computer-based tasks and would take around one hour (some data collected in the current study were used for a different aspect of synaesthesia exploring executive functions, see 52). The term 'synaesthesia' was not mentioned prior to debriefing, and verbal instructions instead referred to 'colour associations'. Participants were told before the study that the aim of the investigation was to explore creativity, mental imagery, colour association, and decision making.

For the tasks administered via computer, a standardised desktop computer (Dell, Core i5, Windows 7, 19" screen) was used on campus, and those off-site used laptops (Toshiba Satellite Oro U500-10K, Windows 7, 14" screen). Both desktop and laptops were calibrated to the same colour and brightness. Participants were seated approximately 50cm from the screen during testing. Task instructions were provided at the start of each task and participants were given the opportunity to ask questions prior to starting each task.

Colour-Picking Consistency Task: This task was designed with two parts to be administered at the start and end of the testing session. The task was done on the computer using a programme written in Adobe Air based upon the grapheme-colour consistency component of the Synaesthesia Battery (53). In the task a series of graphemes were presented to the participant in the top-left corner of the screen with each appearing in black typeface on a neutral white background. A colour selection wheel was presented on the right of the screen (see Figure 1). The colour wheel was arranged with seven concentric rings of increasing brightness toward the centre, each with 24 discrete colours, giving 168 discrete colour shades. Colour shades were at equal intervals in Red-Green-Blue (RGB) colour space. The colour wheel was displayed at random rotations of 0°, 90°, 180° and 270° degrees between trials to prevent participants using a spatial strategy to recall colours. A static vertical greyscale bar to the left of the colour selection wheel facilitated selections of white, black and greyscale, as well as allowing for refinement to the brightness of the colour selected. The colour selection in RGB colour space was recorded for each trial.

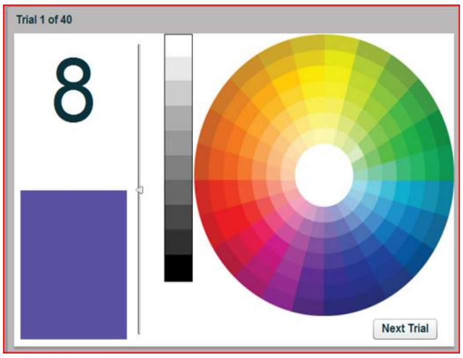

Figure 1: Example screenshot during Colour-Picking Consistency Task

Participants were told that they would be presented with a series of letters and numbers and they should use the mouse to select that colour on the screen which they most closely associate with the letter or number displayed. No explicit time limit was given. Upon selecting a colour, the colour appeared at the bottom left hand side of the screen, and participants had the opportunity to change the colour as required. When satisfied with their selected colour, participants clicked the 'Next trial' to continue.

Part one of the colour-picking consistency task contained two blocks of 20 trials, and Part two had a single block of 20 trials. Each block contained 20 graphemes, comprising all digits 0 through to 9, and three high-frequency (E, T, A), three low-frequency (J, X, Z) and four mid-frequency usage upper-case letters (S, L, M, Q). The same graphemes were tested in a randomised order within the blocks.

Animal Tails Test: A version of the animal tails test (47) was created in E-Prime 2.0 (Psychology Software Tools, Sharpsburg, PA, USA) as a behavioural assessment of mental imagery capability. Pilot testing was used to select the final list of 20 items (See Supplementary Materials). Animals were excluded where there was low consensus in the pilot group or where a tail was a distinct feature of the animal, such as for a beaver or peacock (48). Audio clips in WAV format were prepared with a British male voice pronouncing the animal names in a noise-free environment. The audio clips were then trimmed and volume standardised.

During this task, participants wore headphones, and written instructions were provided on the screen. For each trial, a crosshair fixation appeared in the centre of a white screen for 1000ms, followed by the presentation of the animal name audio. Participants were instructed to visualise the animal 'in their mind's eye' and respond using their dominant hand with a left mouse click if they believed the animal to have a long tail in proportion to their body, and a right-click for a short tail. There was no time limit for the response. These instructions were also displayed in text at the bottom of the screen away from the fixation. There were two practice trials followed by 20 experimental trials. The participant's responses together with reaction time from the onset of each audio clip were recorded.

Mental Rotations Task (MRT-A): The MRT-A (51) is a paper-based task, based upon drawings originally designed by Shepard and Metzler (54). Comprehensive instructions have been provided for the task and were followed closely (51). For each item, one three-dimensional shape is printed on the left of the page and four on the right. Two of the objects on the right are rotations around the vertical axis of the object on the left and two are different objects. The participant is asked to mark the two identical rotations, with a single point given for identifying both correctly. The test has 24 items divided into two parts. Following an example question and untimed practice items, participants had three minutes for each half of the test with an optional break. An interval variable was calculated from the sum of correct answers. Possible scores range from 0 to 24, with a higher score indicating greater mental rotation ability.

Vividness of Visual Imagery Questionnaire (VVIQ): The VVIQ (31) is a self-report scale with 16 items measuring the ability to form clear imagery. Participants are asked to visualise a scene in their 'mind's eye', such as 'a shop to which you often go', and then rate the vividness of the scene on a five-point Likert scale, from 1 ('No image at all, only "knowing" that you are thinking of the object') to 5 ('Perfectly clear and vivid as real seeing'). In some studies, participants complete the form twice, once with eyes open and once with eyes closed whilst visualising the scene. Due to time constraints, participants were asked to complete the questionnaire only once, with their eyes open. An ordinal variable was calculated from the sum of responses. Possible scores range from 16 to 80. High scores on the scale indicate stronger ability to form vivid mental images. Cronbach's alpha in the current study was 0.90.

Spontaneous Use of Imagery Scale (SUIS): The SUIS (33) is a self-report scale with 12 items, measuring the ability to use imagery during daily life. Participants are asked to rate how appropriate each item is to them on a five-point Likert scale from 1 ('Never appropriate') to 5 ('Completely appropriate'). An example of an item is: 'When I think about visiting a relative, I almost always have a clear mental picture of him or her'. An ordinal variable was calculated from the sum of responses. Possible scores range from 12 to 60. High scores on this scale indicated a greater use of imagery in daily life. Cronbach's alpha in the current study was 0.73.

Numeracy measure: A three-item pen-and-paper measure of numeracy was included (55). An example of a question is: 'Imagine that we flip a fair coin 1,000 times. What is your best guess about how many times the coin would come up heads in 1,000 flips?'. The questions concern probability and percentage-proportion conversions. An interval variable was calculated as the total correct responses. Possible scores range from 0, indicating low numerical ability, to 3, indicating high numerical ability.

Intelligence measure (NART): The National Adult Reading Test (NART) (56) was used as a proxy measure of IQ. The NART correlates positively with the Wechsler Adult Intelligence Scale (WAIS, 57) with moderate strength (58). There are 50 words of decreasing frequency, each deemed to have a non-standard English pronunciation. Participants were asked to read aloud slowly through the list, scoring a point for each correct pronunciation. An example of an item from the start of the list is 'ache' and from towards the end is 'sidereal'. An interval variable was calculated as the sum of correct responses. The range of possible scores is 0 to 50.

After completing Part One of the Colour-Picking Consistency Task, participants completed the remaining tasks of the battery, which were divided into three sets. The tasks within each set were reordered between participants in a Latin square design. This design was used to minimise alternation between computer and paper, and reduce the risk of participants tiring. With the tasks concerning the present study in parentheses, the three sets were: 1. Computer-based task (Animal Tails Test); 2. Performance-based paper tasks (MRT-A, NART, Numeracy); 3. Self-report questionnaires (SUIS, VVIQ). Participants then completed the Part Two of the Colour-Picking Consistency Task and provided basic demographic information (age, gender, handedness, education level). Lastly, they were given a brief written questionnaire relating to their knowledge and possible experience of synaesthesia. This provided a basic explanation of synaesthesia ("Synaesthesia can be understood as a blurring or a union of the senses, where two or more senses are automatically joined together in certain circumstances"), followed by questions asking if they had knowledge about synaesthesia before taking part in the study (yes/no), and whether they thought they had synaesthesia (yes/no). Further questions then asked about types of synaesthesia ("numbers or letters have colours", "certain words or letters have certain tastes", "certain sounds make me see shapes", "temporal concepts such as days, months or years have a physical location when I think about them", "letters, numbers or days of the weeks have a distinct personality", or "Other – please describe".

Results

Data Preparation and Descriptive Data

For the Colour-Picking Consistency task a script was written in R version 3.3.0 (59) to produce a consistency score for each participant using Euclidean distances in CIELUV colour space, as recommended by Rothen et al. (46). RGB values for the colours selected across all graphemes, trials and participants were first converted into CIELUV colour space using the 'convertColor' function in base R (59). CIELUV colour space encodes the human perception of colour viewed on computer displays. Euclidean distances measured in CIELUV colour space are closer to colour difference as perceived and are more sensitive in diagnosing synaesthesia than distances in RGB colour space (46). As it was not possible to measure lighting conditions for each participant, D65 (standard daylight) illumination was presumed in the conversion, consistent with the assumption made by Rothen et al. (46). For each grapheme, Euclidean distances in CIELUV colour space were calculated between the three trials (from first trial to second, from second to third, and from first to third). The sum of these three values was calculated for each grapheme.

The means of these values for letters and for numbers were used to create a colour picking consistency for letters score (CPC letters) (M = 194.28, SD = 78.99) and colour-picking consistency for numbers score (CPC numbers) (*M* = 226.51, SD = 84.28). Lower scores indicated a higher level of colour selection consistency, with the lowest score possible being 0 if the participant were to select the same colour shade in each of the three blocks for all graphemes. CPC letters was found to have a negative skew upon inspection of box plots (Shapiro-Wilk p = .033). We decided to use consistency for colours for numbers and letters separately as colours were chosen significantly more consistently for letters than numbers (Z = 3.43, p =.001, r = .41). It is also important to note that synaesthetes can report having colours for numbers and not letters, colours for letters and not numbers, as well as colours for both. Of our 11 participants who indicated that numbers and/or letters have colours, and so potentially may be a grapheme-colour synaesthete, 4 had a CPC Letters score below the threshold of 135 suggested for grapheme-colour synaesthesia consistency (46). In total, 17 (24%) participants had a CPC letters score below 135, and 8 (11%) had a score below 135 on CPC numbers.

For the Animal Tails Task two items were excluded from the final analysis as the correct answers were deemed ambiguous ('sloth' and 'elephant'). Participants were therefore scored out of 18 possible correct answers (See Supplementary Materials for the list of items with response accuracy). Animal Tails reaction times (RT) were calculated as a mean of trials with correct responses, with trials excluded if the response time was under 250ms or over 2.5 standard deviations from the mean for the participant. The mean number of trials excluded per participant was 0.34 (1.7%). Due to a technical error RT data was missing for 18 participants. The Animal Tails Task proportion of errors (PE) was calculated for each participant (*M* = 0.14, SD = 0.12). A significant moderate positive correlation between RT and PE indicated a lack of a speed/accuracy trade-off (r (50) = .40, .*p* = .003). Our key variable for this task was a combination of speed and accuracy, known as an inverse efficiency score (IES, 60), which is calculated using the formula IES = RT / (1-PE). A lower IES indicates better performance on the task. The distribution of IES (*M* = 1868.59, SD = 89.71) had a negative skew (Shapiro-Wilk *p* <.001).

Participant scores were taken as the total number of correct responses for the MRT-A (*M* = 8.63, SD = 4.77), the NART (*M* = 35.61, SD = 5), and numeracy measure (*M* = 2.21, SD = 0.9). A total score for each self-report measure was calculated by summing participants' responses for each item on the VVIQ (*M* = 57.69, SD = 11.81) and SUIS (*M* = 38.56, SD = 8.07).

As we recruited more female participants than male, we explored possible differences in performance across gender. We found a non-significant difference for all variables apart from the MRT-A (Z = 3.07, p = .002) where men (*M* = 9.52, SD = 4.68) scored higher than women (*M* = 6.81, SD = 3.97) and Animal Tails IES (Z = 2.56, p = .018) where men (*M* = 1620.39, SD = 415.83) had a lower IES score than women (*M* = 2036.72, SD = 723.79).

Correlations between key variables

Table 1 shows the correlation coefficients between each of the measurements. CPC letters was found to have a significant moderate positive correlation with the Animal Tails Task IES (*rho* (50) = .49, *p* < .001), meaning that greater colour picking consistency for letters was associated with more accurate and faster responses on this mental imagery task. CPC letters was also found to significantly correlate with CPC number (*rho* (68) = .62, *p* < .001), and a close to significant correlation with the Numeracy score (*rho* (68) = -.23, *p* = .055). With regards to

CPC number, this was found to have a significant moderate correlation with the Animal Tails Test IES (*rho* (50) = .4, *p* = .003), so as with the letters, greater consistency with colour picking for numbers was associated with faster responses on this mental imagery task.

Table 1: Correlation Coefficients (Spearman's Rho) between scores on the Colour Picking Consistency for letters (CPC Letters), Colour Picking Consistency for Numbers (CPC Numbers), Mental Rotation Test accuracy (MRT-A), National Adult Reading Test (NART), Numeracy, Spontaneous Use of Imagery Scale (SUIS), the Vividness of Visual Imagery Questionnaire (VVIQ), Animal Tails Test Inverse Efficiency Score (IES) (N = 70 for all correlations except those including Animal Tails Test IES when N = 52)

	CPC Numbers	MRT-A	NART core	Numeracy Score	SUIS	VVIQ	Animal Tails IES
CPC Letters	.62**	-.15	-.07	-.23	.15	-.17	.49**
CPC Numbers		-.15	-.10	-.12	.05	-.14	.40**
MRT-A			-.01	.31**	-.16	.11	-.40**
NART Score				.07	.06	.21	.12
Numeracy Score					-.33**	-.17	-.15
SUIS						.39**	.15
VVIQ							-.03

Other significant correlations to note include a moderate negative correlation between MRT-A scores and the Animal Tails IES (*rho* (50) = -.4, *p* = .004), suggesting a link between performance on these two tasks. Performance on the MRT-A also significantly correlated with the Numeracy Score (*rho* (68) = .31, *p* = .01), and there was a significant negative correlation between the Numeracy Score and the SUIS (*rho* (68) = -.33, *p* = .006). There was a significant moderate positive correlation between the two mental imagery self-report questionnaires, the SUIS and the VVIQ (*rho* (68) = .39, *p* = .001).

Using measures of mental imagery ability to predict colour picking consistency

We ran two regression models (N = 52)[2] to see how performance on the mental imagery task and scores on the self-report measures would predict 1) CPC Letters and 2) CPC Numbers[3]. For both models we included Animal Tails IES as a predictor variable as this had significant correlations with both outcome variables. We

[2] N = 52 due to the missing RT data. Note that 1 of the 18 participants excluded from the regression model had a CPC letters score less than 135 and subjectively reported experiencing colours with letters (i.e. was 1 of the 4 possible synaesthetes)

[3] We also ran these models with CPC for letters and CPC for numbers calculated when removing trials where participants chose greyscale colours for 2 or 3 of the 3 trials for a grapheme. This was to explore the impact of the possible confound arising from having a static greyscale bar in the colour picking task. Importantly, the results remained the same; the "CPC Letters Adjusted" model was statistically significant (F (4, 47) = 3.74, p = .01), with the predictors explaining slightly less of the variance in CPC Adjusted Letters scores (18% compared to 22%). Animal Tails IES (B =.048, p =.002, BCa 95% CI = 0.017 to 0.09) contributed significantly to the model, whilst the other variables were again not significant contributors. The model for "CPC Numbers Adjusted" remained non-significant.

also included VVIQ and SUIS as predictor variables due to the number of previous studies finding that grapheme-colour synaesthetes report enhanced imagery with these measures (e.g. 38). Scatterplots of these variables can be seen in Figure 2. Furthermore, gender (female coded as 1, male coded as 2) was included as a predictor to control for the impact it can have on mental imagery ability (e.g. see 61), and the gender difference found with the Animal Tails IES with this study. The linear regression was run using IBM SPSS Statistics 25, using the Enter method (default parameters). As residuals in the regression models did not meet the required assumptions for parametric tests, we used BCa bootstrapping, performed 2000 times.

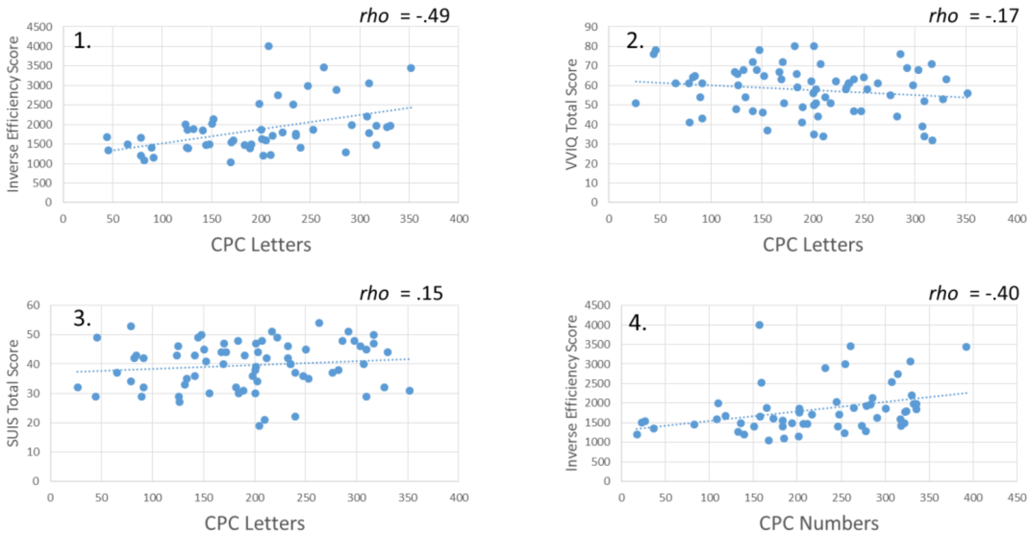

Figure 2: Scatterplots illustrating the significant correlations between a) Colour Picking Consistency (CPC) for letters and Animal Tails Task Inverse Efficiency Score (1), Vividness of Visual Imagery Questionnaire score (2) and Spontaneous Use of Imagery Scale (SUIS) and b) Colour Picking Consistency (CPC) for numbers and Animal Tails Task Inverse Efficiency Score (4).

The results for the CPC Letters model was statistically significant (F (4, 47) = 4.57, p = .003), with the predictors explaining 22% of the variance in CPC Letters scores. Animal Tails IES (B =.053, p =.003, BCa 95% confidence intervals (CI) = 0.02 to 0.09) contributed significantly to the model, while VVIQ score (B = -2.01, p =.033, BCa 95% CI = -3.5 to 0.21), SUIS (B = 1.24, p =.4, BCa 95% CI = -1.1 to 3.64), and gender (B = -1.6, p =.94, BCa 95% CI = -43.25 to 42.07) did not. There was no multicollinearity in the data (VIF scores ranged from 1.13 to 1.26) and the values of the residuals was independent (Durbin-Watson = 2.001). However, the model for CPC Numbers was not statistically significant (F (4, 47) = 2.21, p = .08).[4]

All data used in this analysis is available in Supplementary Materials.

[4] Upon a reviewer's suggestion we ran both models with the MRT variable added as a predictor. In both cases this addition did not change the overall results of the models, MRT did not make a significant contribution to either model.

Discussion

In this study we have explored the relationship between grapheme colour-picking consistency and mental imagery ability. By using a proxy measure of grapheme-colour synaesthesia, we aimed to make a novel contribution to our understanding of synaesthesia and mental imagery. Notably, we used both self-report measures and behavioural assessments of mental imagery ability and mental rotation ability, whilst recruiting participants from the general population, rather than synaesthetes specifically. Overall, we found that consistency in colour-picking for letters could be predicted by performance on a mental imagery task (inverse efficiency score on the Animal Tails Test). The results were not so clear for the colour-picking for numbers, as although the consistency score for numbers significantly correlated with performance on the Animal Tails Task, the regression model was not significant. Interestingly, performance on a mental rotation test, self-report measures of imagery vividness, and image usage were not found to be related to colour-picking consistency for either letters or numbers. We therefore provide novel evidence that greater consistency in colour-picking for letters is associated with enhanced mental imagery ability on an object imagery test, but not spatial imagery. We will discuss how these findings relate to the synaesthesia and mental imagery literature, before going on to consider the implications of using a proxy measure for synaesthesia.

Consistency in picking colours for letters both correlated with, and could be predicted by, performance on the Animal Tails Task (as measured by inverse efficiency score), such that greater consistency in colour choices predicted faster and more accurate performance on the object imagery task. If we take the colour-picking consistency task as a proxy measure for synaesthesia-like behaviour (see below for a discussion of the benefits and drawbacks of such a measure), then this finding adds support to the idea that grapheme-colour synaesthesia is associated with enhanced imagery abilities. With grapheme-colour synaesthesia, this has mainly been based on self-report measures (e.g. 30), with the only behavioural support coming from a study not specifically designed to explore differences in imagery ability, and using a grapheme-based imagery task (29). The current study therefore highlights the need for further exploration of this issue, using a range of imagery tasks. However, another interpretation of the findings may be that those with greater colour-picking consistency have superior memories, meaning they can better remember the colours picked for each grapheme across the trials, and also may perform better on the animal tails task as their superior memory results in more accurate recall of visual information about animals. Future studies would therefore need to include a measure of visual memory to account for such a possibility. Whilst a link between mental imagery and visual memory has been explored, albeit mainly with self-report measures such as the VVIQ rather than behavioural measurements of imagery (62; 63; but see 64 for interesting relationship between colour memory and imagery), the relationship between grapheme-colour synaesthesia and memory has been well documented (see 3 for a review). Consequently, possible links between memory, imagery and synaesthesia are going to be important to pick apart.

The fact that the colour-picking consistency for either letters or numbers was not associated with performance on the mental rotation task is potentially a very interesting finding, if it can be replicated across other tests of mental rotation. Compared to object imagery, the type used in the Animal Tails task, mental rotation has been found to involve very different processes (65; 66). Taking the colour-picking task as a proxy measure of grapheme-colour synaesthesia, this suggests that whilst the current study supports the idea grapheme-colour synaesthetes have enhanced object imagery abilities, they may not have enhanced spatial imagery abilities. If future studies further support this idea, the finding of an advantage in object but not spatial imagery would fit with the ideas currently being proposed about the dorsal/ventral sensory processing streams in relation to synaesthesia. For example, Rothen et al (3) proposed that grapheme-colour synaesthetes' memory advantages may be related specifically to memories relating to the parvocellular rather than magnocellular pathways, as neuroimaging evidence suggests a possible enhanced parvocellular responsiveness in grapheme-colour synaesthesia (1; 67). This difference in sensory processing with stimuli characteristics biased towards the ventral visual pathway may therefore predict any enhanced imagery abilities to be restricted to object rather than spatial imagery. However, further studies are needed using other measures of mental rotation ability (for example see 68 for differences between object-based rotation and egocentric rotation), notwithstanding the need for studies using verified synaesthetes.

Although we had predicted that the imagery self-report measures (the VVIQ and the SUIS) would be associated with the colour picking consistency measure, we did not find evidence to support this. Caution should of course be taken with non-significant results, but it is worth noting that the correlation between SUIS and CPC Letters/CPC Numbers was not even in the direction expected, so it is unlikely due to a simple lack of power. Also, the SUIS does positively correlate with the VVIQ as expected (see 69 for comparison) suggesting that there was nothing unusual about the way our participants completed these measures. Our prediction had been based on the many studies that have found both grapheme-colour and spatial sequence synaesthetes to report greater usage and vividness of imagery (e.g. 38). However, not all studies have found this to be the case, with a recent study by Brang and Ahn (44) finding that, in comparison to non-synaesthetes, grapheme-colour synaesthetes reported greater usage of imagery on the SUIS but not more vivid imagery on the VVIQ. Furthermore, whilst Ward et al (37) found no group difference between non-synaesthetes and sequence-spatial synaesthetes score on the VVIQ2 (70), they also reported that for the non-synaesthetes there was no correlation between their score on the Imagery Ability subscale of the SCSQ (36) and their sequence-space consistency measure. Taken together, these studies suggest that the relationship between synaesthesia (at least grapheme-colour and sequence-space) and imagery self-reports may not be so clear, with potentially other variables such as recruitment bias influencing findings (note that Brang and Ahn employed a double-blind recruitment method). Furthermore, Colizoli et al (71), training a group of non-synaesthetes on a programme that involved reading books with coloured letters, found no correlations between VVIQ score and the colour associations acquired through training.

Eliminating bias in participant recruitment was a key driver in our study design. To this end, participants were recruited from the general population, and we used the colour picking consistency task as a proxy measure of grapheme-colour synaesthesia. As well as helping to reduce demand effects this also had the benefit of potentially recruiting participants who have synaesthesia but may not be aware of it, and so would not normally volunteer to take part in synaesthesia research. Although conscious awareness of grapheme-colour pairings is one of the defining features of grapheme-colour synaesthesia, it is not uncommon to encounter people who have been aware of their own grapheme-colour pairings for as long as they can remember, but do not believe it is a form of synaesthesia because they have incorrectly assumed 'doesn't everyone do that?'. We want to be clear that we are neutral on the suggestion that synaesthesia is on a continuum (for example see 72), which is a complex issue beyond the scope of this study. Rather, we are exploring a way of assessing abilities associated with synaesthesia, without specifically recruiting synaesthete participants. Our method can then be used alongside more traditional methods to help develop a fuller picture of synaesthesia, and see if findings have convergent validity. Interestingly, Rothen et al (73) have recently shown the value of utilising a consistency score as a correlate of their measure of sensory memory, concluding that synaesthetic consistency can be an important individual difference when exploring cognitive correlates of synaesthesia. Of course as well as the benefits, there are important limitations of using a proxy measure of grapheme-colour synaesthesia, and these need to be kept in mind when considering the implications of the current study. In particular, our colour-picking task had some design issues that future studies should note (the reduced number of letters used and greyscale bar not moving location), as potentially these may have artificially inflated participants' consistency scores (although please see footnote in Results section detailing analysis run with recalculated scores in an attempt to explore possible impact of static greyscale bar).

A final note when considering the implications of these findings, is that the study is not suggesting that colour-picking consistency, or even synaesthesia, is caused directly by enhanced mental imagery (or vice versa). Most of the variance in consistency scores is not accounted for by our mental imagery variables. Our data suggest intelligence, numeracy and gender were not related to the colour picking consistency scores, though. Therefore, other factors not considered here such as creativity and personality could also be important, based on previous research (10). We must also note that our findings are limited to letter-colour and number-colour consistency. To gain a fuller picture of mental imagery abilities and their relation to synaesthesia, it would be useful to assess other forms of synaesthesia like music-colour or word-taste.

In conclusion, we report the novel finding that a measure of letter colour-picking consistency can be predicted by performance on an object imagery task in a sample of mainly non-synaesthetes. This result raises some important issues to be considered within synaesthesia research. It suggests that as colour-picking consistency increases, so does mental imagery ability, and so future studies need to further explore this within a synaesthete sample. Furthermore, the fact that this relationship was found with the object imagery task, and not the spatial imagery task, aligns with a possible enhanced parvocellular responsiveness found in grapheme-colour synaesthesia (1). Our study has further highlighted the need to consider recruitment methods used within synaesthesia research (e.g. see 44) as well as the potential utility of using a synaesthesia consistency measure (e.g. see 73) and the importance of using a range of behavioural as well as self-report measures when considering visual mental imagery abilities. Our results strengthen the idea that synaesthesia is associated with enhanced mental imagery, which has important implications for our understanding of synaesthesia itself, and how our perceptual experiences interact with our visual-spatial cognition.

Additional Information

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Ethics

The study was given ethics approval by the School of Psychology Ethics Committee, University of East London, and all participants gave informed consent prior to participation.

Data Accessibility

The datasets supporting this article have been uploaded as part of the Supplementary Material

Authors' Contributions

All authors made substantial contributions to conception and design, and analysis and interpretation of the data. LH and PFM made substantial contribution to acquisition of data. All authors were involved in drafting or revising the article for important intellectual content, and all gave final approval of the version to be published.

Competing Interests

We have no competing interests

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References

1. Barnett KJ, Foxe JJ, Molholm S, Kelly SP, Shalgi S, Mitchell KJ, et al. 2008 Differences in early sensory-perceptual processing in synesthesia: A visual evoked potential study. *NeuroImage* **43**(3):605–13. (10.1016/j.neuroimage.2008.07.028)

2. Banissy MJ, Walsh V, Ward J. 2009. Enhanced sensory perception in synaesthesia. *Exp Brain Res*, **196**, 565-71. (10.1007/s00221-009-1888-0)

3 Rothen N, Meier B, Ward J. 2012. Enhanced memory ability: insights from synaesthesia. *Neurosci Biobehav Rev* **36**:1952–63 (10.1016/j.neubiorev.2012.05.004.)

4. Banissy MJ, Holle H, Cassell J, Annett L, Tsakanikos E, Walsh V, Spiller MJ, Ward J. 2013. Personality traits in people with synaesthesia: Do synaesthetes have an atypical personality profile?. *Personality and Individual Differences*. **54** 828-31 (10.1016/j.paid.2012.12.018).

5. Rouw R, Scholte HS. 2016. Personality and cognitive profiles of a general synesthetic trait. *Neuropsychologia* **88**, 35–48. (10.1016/j.neuropsychologia.2016.01.006)

6 Carmichael DA, Smees R, Shillcock RC, Simner J. 2018. Is there a burden attached to synaesthesia? Health screening of synaesthetes in the general population. *Br J Psychol.* (10.1111/bjop.12354)

7 Carruthers HR, Miller V, Tarrier N, & Whorwell, PJ. 2012. Synesthesia, pseudo-synesthesia, and irritable bowel syndrome. *Digestive Diseases and Sciences*, **57**, 1629–1635 (0.1007/s10620-012-2054-2)

8 Jonas CN, & Hibbard PB. 2015. Migraine in synesthetes and nonsynesthetes: A prevalence study. *Perception*, **44**, 1179–1202. (10.1177/0301006615599905)

9 Simner J, Carmichael DA, Hubbard EM, Morris Z & Lawrie, SM. 2015. Rates of white matter hyperintensities compatible with the radiological profile of multiple sclerosis within self-referred synesthete populations. *Neurocase*, **21**, 322–330. (10.1080/13554794.2014.892625)

10 Chun CA, Hupé JM. 2016. Are synesthetes exceptional beyond their synesthetic associations? A systematic comparison of creativity, personality, cognition, and mental imagery in synesthetes and controls. *Br J Psychol*. **107**. 397-418. (10.1111/bjop.12146)

11 Simner J. 2013. Why are there different types of synesthete?. *Frontiers in Psychology.***4** 558. (10.3389/fpsyg.2013.00558)

12 Pearson J, Naselaris T, Holmes EA, Kosslyn SM. 2015. Mental imagery: functional mechanisms and clinical applications. *Trends in cognitive sciences*. **19**, 590-602 (10.1016/j.tics.2015.08.003).

13 Kosslyn SM, Thompson WL. 2003. When is early visual cortex activated during visual mental imagery?. *Psychological bulletin*. **129**, 723 (10.1037/0033-2909.129.5.723).

14 Nunn JA, Gregory LJ, Brammer M, Williams SC, Parslow DM, Morgan MJ, Morris RG, Bullmore ET, Baron-Cohen S, Gray JA. 2002. Functional magnetic resonance imaging of synesthesia: activation of V4/V8 by spoken words. *Nature neuroscience*. **5**, 371

15 Sperling JM, Prvulovic D, Linden DE, Singer W, Stirn A. 2006. Neuronal correlates of colour-graphemic synaesthesia: AfMRI study. *Cortex*. **42**, 295-303

16 Daselaar SM, Porat Y, Huijbers W, Pennartz CM. 2010. Modality-specific and modality-independent components of the human imagery system. *Neuroimage*. **52**, 677-85 (10.1016/j.neuroimage.2010.04.239)

17 Rouw R, Scholte HS, Colizoli O. 2011. Brain areas involved in synaesthesia: a review. *Journal of neuropsychology*. **5**, 214-42 (10.1111/j.1748-6653.2011.02006.x)

18 van Praag CD, Garfinkel S, Ward J, Bor D, Seth AK. 2016. Automaticity and localisation of concurrents predicts colour area activity in grapheme-colour synaesthesia. *Neuropsychologia.* **88**, 5-14. (10.1016/j.neuropsychologia.2016.04.016)

19 Kosslyn SM, Brunn J, Cave KR, Wallach RW. 1984. Individual differences in mental imagery ability: A computational analysis. *Cognition*. **18**, 195-243. (10.1016/0010-0277(84)90025-8)

20 Zeman A, Dewar M, Della Sala S. 2016 Reflections on aphantasia. *Cortex*. **74**, 336-7.

21 Carmichael DA, Down MP, Shillcock RC, Eagleman DM & Simner J. 2015. Validating a standardised test battery for synesthesia: Does the synesthesia battery reliably detect synesthesia? *Consciousness and Cognition*, **33**, 375–385. (10.1016/j.concog.2015.02.001)

22 Simner J, Mulvenna C, Sagiv N, Tsakanikos E, Witherby SA, Fraser C, Scott K, Ward J. 2006. Synaesthesia: The prevalence of atypical cross-modal experiences. *Perception.***35**, 1024-33 (10.1068/p5469)

23 Deroy O, Spence C. 2013. Why we are not all synesthetes (not even weakly so). *Psychonomic bulletin & review*. **20**, 643-64 (10.3758/s13423-013-0387-2).

24 Jansari AS, Spiller MJ, Redfern S. 2006. Number synaesthesia: When hearing “four plus five” looks like gold. *Cortex*. **42**, 253-8 (10.1016/S0010-9452(08)70350-2).

25 Oertel V, Rotarska-Jagiela A, van de Ven V, Haenschel C, Grube M, Stangier U, Maurer K, Linden DE. 2009. Mental imagery vividness as a trait marker across the schizophrenia spectrum. *Psychiatry Research*. **167** 1-1 (10.1016/j.psychres.2007.12.008).

26 Sack AT, Van De Ven VG, Etschenberg S, Schatz D, Linden DE. 2005. Enhanced vividness of mental imagery as a trait marker of schizophrenia?. *Schizophrenia Bulletin*. **31**, 97-104 (10.1093/schbul/sbi011).

27 Janik McErlean AB, Banissy MJ. 2016. Examining the relationship between schizotypy and self-reported visual imagery vividness in grapheme-color synaesthesia. *Frontiers in psychology*. **7**:131 (10.3389/fpsyg.2016.00131).

28 Vannucci M, Mazzoni G. 2009. Individual differences in object and spatial imagery: Personality correlates. *Personality and Individual Differences*. **46**, 402-5 (10.1016/j.paid.2008.11.003).

29 Spiller MJ, Jansari AS. 2008. Mental imagery and synaesthesia: is synaesthesia from internally-generated stimuli possible?. *Cognition*, **109**, 143-151. (doi:10.1016/j.cognition.2008.08.007)

30 Barnett KJ, Newell FN. 2008. Synaesthesia is associated with enhanced, self-rated visual imagery. *Conscious Cogn*, **17**, 1032-1039. (10.1016/j.concog.2007.05.011)

31 Marks DF. 1973. Visual imagery differences in the recall of pictures. *Br J Psychol*, **64**, 17-24 (10.1111/j.2044-8295.1973.tb01322.x)

32 Price, M. C. 2009. Spatial forms and mental imagery. *Cortex*, ***45***(10), 1229-1245.

33 Reisberg D, Pearson DG, Kosslyn SM. 2003. Intuitions and introspections about imagery: The role of imagery experience in shaping an investigator's theoretical views. *Applied Cognitive Psychology.* **17**, 147-60 (10.1002/acp.858).

34 Blajenkova O, Kozhevnikov M, Motes MA. 2006. Object-spatial imagery: a new self-report imagery questionnaire. *Applied Cognitive Psychology* **20**, 239-63 (10.1002/acp.1182)

35 Havlik AM, Carmichael DA, Simner J. 2015. Do sequence-space synaesthetes have better spatial imagery skills? Yes, but there are individual differences. *Cogn Process*, **16**, 245-253. (https://doi.org/10.1007/s10339-015-0657-1)

36 Mealor AD, Simner J, Rothen N, Carmichael DA, Ward J. 2016. Different dimensions of cognitive style in typical and atypical cognition: new evidence and a new measurement tool. *PloS one*. **11**(e0155483. (10.1371/journal.pone.0155483)

37 Ward J, Ipser A, Phanvanova E, Brown P, Bunte I, Simner J. 2018. The prevalence and cognitive profile of sequence-space synaesthesia. *Consciousness and cognition*. **31**, 79-93 (10.1016/j.concog.2018.03.012).

38 Spiller MJ, Jonas CN, Simner J, Jansari A. 2015. Beyond visual imagery: How modality specific is enhanced mental imagery in synesthesia? *Conscious Cogn*, **31**, 73-85. (10.1016/j.concog.2014.10.010)

39 Allbutt J, Ling J, Rowley M, Shafiullah M. 2011. Vividness of visual imagery and social desirable responding: correlations of the vividness of visual imagery questionnaire with the balanced

inventory of desirable responding and the Marlowe–Crowne scale. *Behavior research methods*. **43**, 791 (10.3758/s13428-011-0086-8).

40 Fulford J, Milton F, Salas D, Smith A, Simler A, Winlove C, Zeman A. 2018. The neural correlates of visual imagery vividness–An fMRI study and literature review. *Cortex.* **105** 26-40 (10.1016/j.cortex.2017.09.014).

41 Brang D, Miller LE, McQuire M, Ramachandran VS, Coulson S. 2013. Enhanced mental rotation ability in time-space synesthesia. *Cogn Process*, **14**, 429-434. (https://doi.org/10.1007/s10339-013-0561-5)

42 Simner J, Mayo N, Spiller MJ. 2009. A foundation for savantism? Visuo-spatial synaesthetes present with cognitive benefits. *Cortex,* **45**,1246–1260. (10.1016/j.cortex.2009.07.007)

43 Rizza, A., & Price, M. C. (2012). Do sequence-space synaesthetes have better spatial imagery skills? Maybe not. *Cognitive Processing*, **13**, 299-303.

44 Brang D, Ahn E. 2019. Double-Blind Study of Visual Imagery in Grapheme-Color Synesthesia. *Cortex*. **117** 89-95. (doi.org/10.1016/j.cortex.2019.02.025)

45 Nichols AL, Maner JK. 2008. The good-subject effect: Investigating participant demand characteristics. *The Journal of general psychology*. **135** 151-66 (10.3200/GENP.135.2.151-166).

46 Rothen N, Seth AK, Witzel C, Ward J. 2013. Diagnosing synaesthesia with online colour pickers: maximising sensitivity and specificity. *Journal of neuroscience methods*. **215** 156-60 (10.1016/j.jneumeth.2013.02.009).

47 Farah MJ, Levine DN, Calvanio R. 1988. A case study of mental imagery deficit. *Brain and cognition*. **8** (147-64 10.1016/0278-2626(88)90046-2).

48 Pearson DG, Deeprose C, Wallace-Hadrill SMA, Heyes SB, & Holmes EA. 2013. Assessing mental imagery in clinical psychology: A review of imagery measures and a guiding framework. *Clinical Psychology Review*, **33**, 1–23 (10.1016/j.cpr.2012.09.001)

49 Behrmann M, Moscovitch M, & Winocur G. 1994. Intact visual imagery and impaired visual perception in a patient with visual agnosia. *Journal of Experimental Psychology: Human Perception and Performance*, **20**, 1068–1087.

50 Moro V, Berlucchi G, Lerch J, Tomaiuolo F, Aglioti SM. 2008. Selective deficit of mental visual imagery with intact primary visual cortex and visual perception. *Cortex*. **44**, 109-18.

51 Peters M, Laeng B, Latham K, Jackson M, Zaiyouna R, Richardson C. 1995. A redrawn Vandenberg and Kuse mental rotations test-different versions and factors that affect performance. *Brain and cognition*. **28**, 39-58. (10.1006/brcg.1995.1032)

52 Keshani I, Spiller MJ, Jonas CN, Thoma V. In prep. Trait grapheme-colour synaesthesia and improved executive functions.

53 Eagleman DM, Kagan AD, Nelson SS, Sagaram D, Sarma AK. 2007. A standardized test battery for the study of synaesthesia. *J Neurosci Methods*, **159**, 139–145. (10.1016/j.jneumeth.2006.07.012)

54 Shepard RN, Metzler J. (1971) Mental rotation of three-dimensional objects. *Science.* **171** 701-3 (10.1126/science.171.3972.701).

55 Schwartz LM, Woloshin S, Black WC, Welch HG. 1997. The role of numeracy in understanding the benefit of screening mammography. *Annals of internal medicin*e. **127** 966-72 (10.7326/0003-4819-127-11-199712010-00003).

56 Nelson HE, Willison J. 1991. National adult reading test (NART). Windsor: Nfer-Nelson

57 Wechsler D. 1955. Manual for the Wechsler adult intelligence scale.

58 Bright P, Jaldow EL, Kopelman MD. 2002. The National Adult Reading Test as a measure of premorbid intelligence: a comparison with estimates derived from demographic variables. *Journal of the International Neuropsychological Society*. **8** 847-54 (10.1017/S1355617702860131).

59 R Core Team. 2016 R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.r-project.org/

60 Townsend JT, & Ashby FG. Methods of modelling capacity in simple processing systems. In Castellan, NJ Restle F, eds. Cognitive theory. Hillsdale, NJ: Lawrence Erlbaum, 1978. p. 199–239.

61 Palermo L, Piccardi L, Nori R, Giusberti F, Guariglia C. 2016. The impact of ageing and gender on visual mental imagery processes: A study of performance on tasks from the Complete Visual Mental Imagery Battery (CVMIB). *Journal of clinical and experimental neuropsychology*. **38** 752-63 (10.1080/13803395.2016.1161735).

62 Cohen BH, Saslona M. 1990. The advantage of being an habitual visualizer. *Journal of Mental Imagery* **14**, 101–112.

63 McKelvie SJ. 1994 The Vividness of Visual Imagery Questionnaire as a predictor of facial recognition memory performance. *Brit J of Psychol*. **85**, 93-104.

64 Heuer F, Fischman D, Reisberg D. 1986. Why does vivid imagery hurt colour memory?. *Canadian Journal of Psychology/Revue canadienne de psychologie*. **40**, 161

65 Mast FW, Kosslyn SM. 2002. Visual mental images can be ambiguous: Insights from individual differences in spatial transformation abilities. *Cognition.* **86** 57-70. (10.1016/S0010-0277(02)00137-3)

66 de Vito S, Buonocore A, Bonnefon JF, Della Sala S. 2014. Eye movements disrupt spatial but not visual mental imagery. *Cognitive processing*. **15** 543-9 (doi.org/10.1007/s10339-014-0617-1).

67 Banissy MJ, Stewart L, Muggleton NG, Griffiths TD, Walsh VY, Ward J, Kanai R. 2012. Grapheme-color and tone-color synesthesia is associated with structural brain changes in visual regions implicated in color, form, and motion. *Cognitive Neuroscience*, **3**, 29–35. https://doi.org/10.1080/17588928.2011.594499.

68 Hegarty M, Waller D. 2004. A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*. **32** 175-91 (10.1016/j.intell.2003.12.001).

69 Nelis S, Holmes EA, Griffith JW, Raes F. 2014. Mental imagery during daily life: Psychometric evaluation of the Spontaneous Use of Imagery Scale (SUIS). *Psychologica Belgica.* **54** 19 (10.5334/pb.ag).

70 Marks DF. 1995. New directions for mental imagery research. *Journal of Mental Imagery*, **19**, 153–167.

71 Colizoli O, Murre JM, Scholte HS, van Es DM, Knapen T, Rouw R. (2016) Visual cortex activity predicts subjective experience after reading books with colored letters. *Neuropsychologia*. **88** 15-27 (10.1016/j.neuropsychologia.2015.07.006).

72 Simner J. 2012 Defining synaesthesia: a response to two excellent commentaries. *Br J Psychol* **103** 24-7. (10.1111/j.2044-8295.2011.02059.x)

73 Rothen N, Seth AK, & Ward J. 2018. Synesthesia improves sensory memory, when perceptual awareness is high. *Vision Research*, 153, 1-6 (doi.org/10.1016/j.visres.2018.09.002)