PERCEPTUAL DISSIMILARITY ANALYSIS DISTINGUISHES GRAPHEME-COLOR SYNESTHETES FROM NON-SYNESTHETES

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ABSTRACT

Synesthetes can be distinguished from non-synesthetes on a variety of experimental tasks because their concurrent synesthetic experiences can affect task performance if these experiences match or conflict with some aspect of the stimulus. Here, we tested grapheme-color synesthetes and non-synesthetic control participants using a novel perceptual similarity task to assess whether synesthetes' concurrent color experiences influence perceived grapheme similarity. Participants iteratively arranged graphemes and, separately, their associated synesthetic colors in a display, such that similar items were placed close together and dissimilar items further apart. The resulting relative inter-item distances were used to calculate the pair-wise (dis)similarity between items in the set, and thence to create separate perceptual representational dissimilarity matrices (RDMs) for graphemes and colors, on an individual basis. On the assumption that synesthetes' similarity judgments for graphemes would be influenced by their concurrent color experiences, we predicted that grapheme and color RDMs would be more strongly correlated for synesthetes than non-synesthetes. We found that the mean grapheme-color RDM correlation was indeed significantly higher in synesthetes than non-synesthetes; in addition, synesthetes' grapheme-color RDM correlations were more likely to be individually statistically significant, even after correction for multiple tests, than those of non-synesthetes. Importantly, synesthetes' grapheme-color RDM correlations scaled with the consistency of their grapheme-color associations as measured by their Synesthesia Battery (SB) scores. By contrast, the relationship between SB scores and grapheme-color RDM correlations for non-synesthetes was not significant. Thus, dissimilarity analysis quantitatively distinguished synesthetes from non-synesthetes, in a way that meaningfully reflects a key aspect of synesthetic experience.

INTRODUCTION

Synesthesia is a phenomenon in which percepts of ordinary stimuli, such as graphemes (written letters and numbers), known as 'inducers', are accompanied by involuntary, unrelated, secondary experiences, such as colors, referred to as 'concurrents' (Novich et al., 2011; Simner, 2012; Ward, 2013). In addition to being involuntary, these synesthetic associations are also arbitrary (i.e., there is no apparent reason why 'A' should evoke purple), idiosyncratic (i.e., different synesthetes may associate different colors with the same grapheme), and remain consistent over time (Simner, 2012; Ward, 2013).

Because synesthetic concurrents arise automatically and cannot usually be actively suppressed (Mattingley et al., 2001; Lupiáñez & Callejas, 2006), they can affect performance on some tasks in ways that distinguish synesthetes from non-synesthetes. For example, in the Stroop (1935) paradigm, grapheme-color synesthetes are faster to name the displayed color of a grapheme if it matches the concurrent color they experience for that grapheme, but slower if the displayed and concurrent colors are mismatched (Mattingley et al., 2001; Elias et al., 2003; Cohen Kadosh & Henik, 2006; Lupiáñez & Callejas, 2006). In priming paradigms, synesthetes are similarly slower to name a target color if it is primed by a grapheme that induces a synesthetic color that is incongruent with the target real color (Elias et al., 2003; Alvarez & Robertson, 2013). In a recent study from our group, synesthetes were slower to respond, compared to non-synesthetes, on the Implicit Association Test (IAT) during blocks of trials pairing graphemes with displayed colors that were incongruent with synesthetic colors (Lacey et al., 2021).

Here, we tested perceptual similarity judgments as a novel way of distinguishing grapheme-color synesthetes from non-synesthetes, using a task in which participants were asked to arrange graphemes and, separately, the associated synesthetic colors, according to their perceived similarity. Thus, the task avoids conflicts between the synesthetic and display colors of a grapheme, as in the Stroop task (Mattingley et al., 2001; Elias et al., 2003; Cohen Kadosh & Henik, 2006; Lupiáñez & Callejas, 2006); between incongruent synesthetic and real color primes and targets (Elias et al., 2003; Alvarez & Robertson, 2013); and between incongruent synesthetic and real color response key associations (Lacey et al., 2021). The perceptual similarity task is a form of multidimensional scaling in which items are iteratively arranged in a display so that similar items are placed closer together and dissimilar items further apart (Kriegeskorte & Mur, 2012: Figure 1a). The resulting inter-item distances are used to form representational dissimilarity matrices (RDMs) in which the values in each cell estimate the pair-wise (dis)similarity of the items in the set (Kriegeskorte & Mur, 2012: Figure 1b).

The assumption is that, given neutral instructions about what feature(s) to use, synesthetes will be influenced by their concurrent color experiences in their similarity judgments of graphemes. Synesthetically experienced colors are as 'real' as actually perceived colors in the sense that both facilitate visual search and grouping, i.e. synesthetic colors behave like real colors (see Kim et al., 2006). Thus, to the extent that synesthetes incorporate synesthetic color information into their similarity judgments of graphemes, their grapheme RDMs should resemble their RDMs for those colors when presented as real colors. This resemblance, a measure of how strongly perceptual similarity judgments of graphemes are influenced by concurrent synesthetic experiences of color, can be quantified as the correlation between grapheme and color RDMs (Figure 1c).

In order to understand how our perceptual similarity analysis might reflect other aspects of synesthetic experience, we examined its relationship to the consistency of synesthetic associations as measured by scores on the Synesthesia Battery (SB: Eagleman et al., 2007), reasoning that high consistency in the evoked synesthetic colors would result in a consistent influence on similarity judgments of graphemes across trials, and to scores on the Projector-Associator (PA) questionnaire (Rouw & Scholte, 2007). Synesthetes are divided into 'projector' synesthetes, who 'see' their concurrent in external space, perhaps as an 'aura' around a grapheme; and 'associator' synesthetes, who experience their concurrent internally, perhaps in their mind's eye or as a strong feeling of association (Dixon et al., 2004). We hypothesized that, compared to associators, projectors' similarity judgments of graphemes would be more likely to be influenced by their synesthetic colors if these were experienced as, for instance an aura around the grapheme or overlaid onto it (see Ward et al., 2007), while they performed the grapheme similarity task.

MATERIALS & METHODS

Participants

Forty people took part in this study: 20 were grapheme-color synesthetes (identified based on their SB scores – see below) and 20 were age- and gender-matched non-synesthetic control participants (18 females, 2 males in each group; mean age: synesthetes 28 years and 9 months, non-synesthetes 29 years; the mean ages were not significantly different [$t_{38} = -.06$, $p = .9$]). This study was conducted online during the COVID-19 pandemic; all participants gave verbal informed consent via a phone or Zoom call, and all procedures were approved by the Penn State College of Medicine Institutional Review Board.

Synesthesia Battery

Participants who claimed to experience grapheme-color synesthesia completed the SB (Eagleman et al., 2007) in order to verify their synesthetic status. The SB reliably identifies certain common varieties of synesthesia (Carmichael et al., 2015). For grapheme-color synesthesia associated with the Latin alphabet and Arabic numerals, all 36 graphemes are presented three times in random order and the participant uses a color-picker to select the best match for the color they experience for that grapheme. Color-picker responses are converted to a single SB score. During data collection, the SB became unavailable online. As a replacement, we administered the MATLAB version available via the TexSyn toolbox (Eagleman et al., 2007) and downloaded from www.synesthete.org prior to its going offline; this is not the full version of the SB, but enabled us to obtain scores for grapheme-color synesthesia. The Texsyn toolbox version was administered to 13 of the 20 synesthetes and 19 of the 20 non-synesthetic control participants.

An individual is considered a synesthete if their SB score is less than 1 and a non-synesthete if their score is more than 2; where an individual's score falls between 1 and 2, their synesthetic status cannot be reliably determined (Eagleman et al., 2007). However, the threshold of 1 for classifying synesthetes need not be considered an absolute cut-off since SB scores "vary along a distribution" (Eagleman et al., 2007, p142) and represent incremental differences among a range of possible scores (Carmichael et al., 2015). A more recent analysis of grapheme-color synesthesia proposes a higher threshold of 1.43 (Rothen et al., 2013; Anderson & Ward, 2015) and this higher threshold reveals numbers of synesthetes more in line with prevalence estimates (Carmichael et al., 2015). Thus, we adopted 1.43 as the cut-off and included as synesthetes three participants with SB scores of 1.08, 1.13, and 1.29, who only showed high consistency for a limited number of graphemes. Thus, for synesthetic participants, SB scores ranged from 0.35 to 1.29.

Non-synesthetic control participants also completed the SB and, for each grapheme, were asked to choose the color they would associate with that grapheme if they had to make a choice. These instructions were uninformative as to what that color might be and, in particular, control participants were not told to pick a color and try to remember it over the course of SB completion which might have encouraged the use of mnemonic strategies (i.e., b = blue, g = green, o = orange, and so on, to create associations. Note that such organized associations can influence grapheme-color associations for both synesthetes and non-synesthetes [Simner et al., 2005], but only synesthetes actually experience color as a concurrent percept). All non-synesthetes' SB scores were above 2 (mean ± SEM: 2.8 ± 0.07) and were significantly higher than those for the synesthete group (0.7 ± 0.06: $t_{38} = -23.4$, $p < .001$, $d = 7.4$). Thus, SB scores differentiated robustly between synesthetes and non-synesthetes.

Perceptual similarity analysis

<u>Stimuli</u>

From each synesthete's SB data, we chose 8 graphemes, balancing the need for selections with high consistency with, where possible, a mix of graphemes that were similar in shape but differing in their associated colors, and graphemes that differed in shape but associated with similar colors. We also created 8 color stimuli corresponding to the synesthete's concurrent color experience for each of the chosen graphemes. Thus, each synesthete had a different set of graphemes and colors; non-synesthetic control participants were presented with the grapheme and color sets (8 in each set) of the synesthete for whom they were an age- and gender-match. Having the controls use the same graphemes and colors as the synesthete to whom they were matched increases the likelihood that group differences are due to synesthesia and not stimulus properties (Ásgeirsson et al., 2015).

Graphemes were displayed in Courier New typeface and colors as colored squares. The font size was set such that grapheme height was 5% of the width of the field of view and the dimensions of the color squares matched this. As noted above, the SB records three estimates of the synesthetic color for each grapheme and there was no way of knowing which of these was closest to the synesthete's actual experience. Since we selected graphemes with high consistency between these three estimates (but not necessarily, as above, the *most* consistency), we used the average of these RGB values to prepare the color stimuli.

Online similarity task

The perceptual similarity task was presented on the Meadows online platform (https://meadows-research.com/) and was performed twice, once for graphemes and once for colors. As synesthetes might have been primed by the color task, all participants performed the grapheme task first, followed by the color task.

For both tasks, items were initially presented around, but outside, the circumference of a circular 'arena' and participants placed items within the arena using a computer mouse to drag-and-drop items. Participants were instructed to "arrange the [letters/colors] according to how similar they look" and that similar items should be placed closer together than dissimilar items. Thus, the task instructions were uninformative as to the particular visual dimension(s) on which participants should base their similarity judgments. These neutral instructions ensured that all participants received the same guidance on how to perform the task, and avoided biasing task performance towards either the shape of the graphemes or their associated synesthetic colors. The instructions remained on-screen, above the arena, throughout each trial of each task (Figure 1a).

All 8 items were presented on the first trial and an initial estimate of the RDM was calculated from the relative inter-item distances, i.e., the on-screen distance ratios are assumed to reflect the dissimilarity ratios. Subsequent trials presented subsets of items that were adaptively selected to re-test dissimilarities for which the last estimate of the RDM provided the weakest evidence. On each trial, after all items had been placed within the arena to the participant's satisfaction, clicking on a green button marked "finish" advanced the task to the next trial. This procedure continued until either a preset evidence weight threshold, or a time limit, was reached. (For a full description of the method, please see Kriegeskorte & Mur, 2012). In order to obtain a good estimate of the final RDM, we set an evidence weight threshold of 0.8; pilot testing indicated that for a set size of 8 items, 10 minutes was a sufficient time to reach this threshold. For the main experiment, however, we set the task to time out at 15 minutes on the basis that synesthetes might take longer over the task. All participants reached the required evidence weight threshold of 0.8 well within the time allowed.

The final RDMs consisted of an 8 x 8 matrix in which the values in each cell estimated the pair-wise (dis)similarity of all items in the set; the matrix was symmetric across the diagonal (Figure 1b). The correlation between grapheme and color RDMs was derived by vectorizing one half of the off-diagonal data in each RDM and computing the Spearman correlation between the two vectors (Figure 1c). The degrees of freedom (df) for correlations are given by N-2; for the correlations between the grapheme and color RDMs, this is adapted to $((N^2 - N)/2) - 2$, where N^2 gives the size of the matrix, - N removes the diagonal cells, and dividing by 2 removes the redundant half of the cells, the matrices being symmetric across the diagonal (Lacey et al., 2020): for an 8 x 8 matrix, df = 26.

Relationship of perceptual similarity judgments to other measures of synesthesia

Of primary interest was whether the grapheme RDM to color RDM correlations reflected SB scores, which essentially measure the consistency of synesthetic associations. In addition, we also compared the results of the perceptual similarity task to scores on the Projector-Associator questionnaire (PA: Rouw & Scholte, 2007). The PA questionnaire consists of six descriptive statements each for projectors and associators; participants rate how strongly these statements match their experience on a 5-point Likert scale. The mean of the associator responses is deducted from the mean of the projector responses (P-A) to give a single score: negative values indicate the associator subtype and positive values indicate the projector subtype.

Data analysis

Data were analyzed using IBM SPSS v27 (IBM Corporation, Armonk NY) and effect sizes (Cohen’s d) were calculated using the online tool provided by Lenhard & Lenhard (2016).

RESULTS

Perceptual similarity analysis

At the group level, the mean (± SEM) Spearman correlation (r_s) between grapheme and color RDMs was significantly larger for synesthetes (0.42 ± 0.07) compared to non-synesthetes (-.012 ± .05; $t_{38} = 4.9$, $p < .001$, d = 1.5). Since Spearman correlation coefficients may not be normally distributed, we confirmed this result with the non-parametric Mann-Whitney test (U = 54.0, z = -3.9, $p < .001$, d = 1.5).

For the group mean analysis reported above, it was not necessary that grapheme-color RDM correlations were individually statistically significant. However, it is worth noting that, compared to the non-synesthetes, more synesthetes showed correlations that were statistically significant at an uncorrected α of $p < .05$ (synesthetes: 10/20, non-synesthetes: 1/20; $\chi^2 = 10.16$, p = .001, d = 1.17). Furthermore, 8 of these 10 synesthetes’ correlations that were significant individually also passed a Bonferroni-corrected α of p = .0025 (corrected for 20 tests), whereas the sole non-synesthete’s correlation did not (note that, because of this zero-value, the related χ^2 statistic cannot be calculated). Relatedly, it was not necessary for the group analysis that the grapheme-color RDM correlations were significantly different on a pair-wise basis between synesthetes and their matched controls. This correlation was larger for the synesthete than their control in 15 of the 20 pairs and significantly so for 7 pairs using the Fisher Z-transform test ($p < .05$ in each case).

Finally, we examined whether synesthetes and controls differed either in the time taken to complete the similarity task or the number of trials required to reach the given evidence weight threshold. The only significant effect was that the grapheme similarity task took longer than the color task (384 ± 28 s vs 276 ± 22 s respectively; $F_{1,38} = 31.7$, $p < .001$); there were no significant differences between synesthetes and controls, nor interactions between synesthetic status and task type, for either the time to complete the task or the number of trials required to reach the evidence threshold (all $F_{1,38} < 1.3$, all $p > .28$).

Relationship between perceptual similarity judgments and other measures of synesthetic experience

We examined the correlation across individuals between SB scores and the grapheme-color RDM correlation, separately for synesthetes and non-synesthetes (Bonferroni-corrected α for 2 tests = .025). Synesthetes' SB scores and grapheme-color RDM correlations were strongly negatively correlated ($r_{s\ 18} = -.54$, $p = .01$: Figure 2) but for non-synesthetes this relationship was not significant ($r_{s\ 18} = .23$, $p = .3$: Figure 2). Thus, as synesthetes' SB scores decreased (indicating greater consistency of synesthetic associations), the grapheme-color RDM correlation increased (implying that the influence of color concurrents on the perceived similarity of graphemes increased).

Since synesthetes were only tested on a subset of their grapheme-color associations, we also calculated the SB score for the subsets (Subset SB). A caveat here is that the 8 graphemes were chosen to ensure that there were some that were similar in shape but differed in color and vice versa – this avoided biasing similarity judgments to either of these factors (see 'Stimuli' above). As a result, the subset does not necessarily sample the *most* consistent associations and therefore the Subset SB may not give a true measure of consistency. Nonetheless, the Subset SB score closely tracked the full SB score ($r_{s\ 18} = .76$, $p < .001$, Figure 3); but the Subset SB/grapheme-color RDM correlation fell short of significance ($r_{s\ 18} = -.38$, $p = .09$), although it was not significantly different from the full SB/grapheme-color RDM correlation of -.54 (Fisher Z = .6, p = 0.5).

Finally, we explored how the grapheme-color RDM correlation was related to scores on the PA questionnaire. In line with the general finding that the projector subtype is less common than the associator subtype (Dixon & Smilek, 2005), our sample comprised 4 projector and 14 associator synesthetes. One synesthete did not complete the PA questionnaire and one had a PA score of 0, suggesting that this individual experienced a mixture of projected and associated synesthetic colors and reflecting the idea that the projector/associator subtypes are neither dichotomous nor along a linear continuum (Anderson & Ward, 2015). This being the case, it was perhaps unsurprising that there was no significant correlation between PA scores and the grapheme-color RDM correlation ($r_{s\ 17}$ = .15, p = .5). The mean grapheme-color RDM correlation was slightly higher for projectors (.43) than associators (.4) but not significantly so (Welch's t-test for unequal sample sizes: t' = .12, df = 3.97, p = .45 [1-tailed, as we have a directional hypothesis that projectors are advantaged on the sorting task]; computed using the online calculator provided by Gaetano, 2019).

Post-experiment follow-up

Fourteen synesthetes and seven control participants responded to a post-experiment debrief. The color stimuli were based on the average of the three sets of RGB values for each grapheme (see 'Stimuli' above); 9 of the 14 synesthetes reported that the color stimuli were a good match for their synesthetic colors associated with the selected graphemes, 3 reported that they were a reasonable match (2 did not respond or did not recall: DNR). Neither synesthetes nor non-synesthetes reported using a mnemonic strategy for color associations when completing the SB: synesthetes reported that this was unnecessary because they had concurrent experiences of color anyway, while 5 non-synesthetes reported that they chose colors more or less randomly for each grapheme (DNR = 2).

The key difference between synesthetes and controls was their approach to arranging graphemes in the similarity task when the task instructions were neutral (see 'Online similarity task' above). All control participants reported using shape information alone and not color – as would be expected for a group that did not experience synesthetic colors. By contrast, only one synesthete reported using predominantly shape information; 5 reported using a combination of shape and synesthetic color information; and 7 reported that they could not avoid using predominantly their synesthetic color information (DNR = 1). Thus, concurrent experiences of synesthetic colors influenced judgments of grapheme similarity for the majority of synesthetes.

In addition, all control participants reported that, when completing the grapheme similarity task, they were unable to recall the colors they had chosen when completing the SB – unsurprisingly, since these were apparently chosen randomly. This suggests that presenting control participants with the colors for their matched synesthete was functionally equivalent to the random choices they made for the SB. We return to this point in the Discussion.

DISCUSSION

Value of perceptual dissimilarity analysis in synesthesia

The present study is the first to use the multi-arrangement method of measuring pair-wise (dis)similarity between the items in a set (Kriegeskorte & Mur, 2012; Majewska et al., 2020) to distinguish synesthetes from non-synesthetes. We reasoned that, since grapheme-color synesthetes are generally unable to suppress their concurrent color experiences, these would influence their judgment of the visual similarity of graphemes. As predicted, the mean correlation between grapheme and color RDMs was significantly higher in synesthetes than non-synesthetes. In addition, in our sample, grapheme-color RDM correlations were consistently positive for synesthetes, whereas for non-synesthetes these correlations were as likely to be negative as positive, with a mean value near zero. Moreover, compared to non-synesthetes, grapheme-color RDM correlations for synesthetes were more likely to be individually statistically significant, even after Bonferroni-correction for multiple tests. Thus, dissimilarity analysis successfully distinguished synesthetes from non-synesthetes. Moreover, these results advance our understanding of synesthesia by enabling us to *quantify* the influence of concurrent color experiences on perception of the inducing grapheme stimuli by reference to the strength of the correlation between the grapheme and color RDMs. The influence of concurrent colors on tasks involving grapheme perception is perhaps best known from reports of a ‘pop-out’ effect in an embedded figures test (Ramachandran & Hubbard, 2001a, 2001b)[1]. But, as Rich & Karstoft (2013, Footnote 1, p116) point out, it can be difficult to quantify individual differences in the magnitude of the effect. One prediction here would be that faster response times on the embedded figures test would scale with scale with increasing task influence of concurrent colors, i.e., a stronger correlation between grapheme and color RDMs.

In this study, synesthetic status was established using the SB score, a measure of the consistency of synesthetic associations. The effect sizes for the differences between synesthetes and non-synesthetes were large (d = 1.5 for the mean grapheme-color RDM correlation, and 1.17 for the number of individual grapheme-color RDM correlations that were statistically significant). These values are comparable to other studies using consistency measures and for differences on a variety of tasks, including spontaneous use of visual imagery (Brang & Ahn, 2019, d = 1.39; Spiller et al., 2015, d = 1.15, cited in and calculated by Brang & Ahn, 2019), recognition memory (Ward et al., 2013, d = 1.0[2]), sensitivity to the crossmodal pseudoword-shape correspondence (Lacey et al., 2016, d = 1.3), and grapheme-color congruency magnitudes on the IAT (Lacey et al., 2021, d = 1.9): note that, apart from Lacey et al. (2016), these effect sizes are, as here, specifically for groups of grapheme-color synesthetes.

Participants received neutral task instructions to arrange graphemes and colors “according to how similar they look”; these were therefore uninformative as to which particular visual

[1] In this task, a specific grapheme, e.g., ‘T’, was used to create an outline shape, e.g., a circle, embedded in a field of different, randomly placed, distractor graphemes, e.g., ‘B’s and ‘M’s. For synesthetes, detection of the shape is facilitated by the synesthetic color for ‘T’ standing out against the background of the colors for the distractor graphemes whereas, for non-synesthetes, detection of the shape is more difficult because they only perceive a set of monochrome graphemes (Ramachandran & Hubbard, 2001a).

[2] Calculated from the statistical information reported, using the online calculator provided by Lenhard & Lenhard (2016).

dimension participants should use in making their similarity judgments. Such neutral instructions ensured that all participants received the same guidance and avoided biasing task performance. For example, prompting the use of color when sorting graphemes might have biased synesthetes to concentrate on their concurrent color experiences, potentially overestimating the effect (or even producing a spurious effect), while simultaneously meaning nothing to non-synesthetic participants, who lack synesthetic experiences. It is worth noting that explicitly instructing participants to arrange graphemes by shape would also have placed all participants on the same footing by directing them to use information equally available to both synesthetes and non-synesthetes. If our findings were replicated under these conditions, this would support the automaticity of the influence of synesthetic concurrent experiences on judgments of grapheme similarity. The potential automaticity of this influence is worth exploring in future work especially since synesthetes appeared to differ in the balance between their color experiences and shape information in forming similarity judgments (see ‘Post-experiment follow-up’ above).

Dissimilarity analysis in relation to other measures of synesthetic experience

As a measure of the convergent validity (i.e., the extent to which test performance is correlated with factors that should, in principle, be related) of the perceptual similarity method, grapheme-color RDM correlations for synesthetes scaled with their SB scores, a measure of the consistency of synesthetic experiences: higher consistency was associated with stronger grapheme-color RDM correlations. By contrast, non-synesthetes, whose SB scores reflect very little consistency in grapheme-color associations, showed a much weaker and non-significant relationship between their SB scores and their grapheme-color RDM correlations. We infer that, in arranging graphemes according to their perceived visual similarity, synesthetes were influenced by the concurrent color experiences that accompanied each grapheme, even though the task instructions were uninformative as to the particular visual dimension(s) on which they should base their similarity judgments. Since the grapheme-color RDM correlations scaled with their SB scores, synesthetes’ similarity judgments likely reflected the consistency of their grapheme-color associations, particularly as graphemes could be presented multiple times during the similarity judgment task. In addition to the conventional, overall, SB score, we calculated the score for the subset of graphemes that were tested. The Subset SB and full SB scores were strongly correlated, indicating that the Subset SB score mirrored synesthetic status, but the correlation between the Subset SB score and the grapheme-color RDM correlation failed significance. This no doubt reflected the fact that grapheme subset selections were not based solely on consistency and that therefore the Subset and full SB scores were not directly comparable. Nonetheless, the Subset SB/grapheme-color RDM correlation was not significantly different from the main correlation result and we therefore consider that the main result and the Subset SB result are in broad agreement.

The SB tests the consistency of synesthetic associations; scores below a given threshold (either 1: Eagleman et al., 2007, or 1.43: Rothen et al., 2013; Anderson & Ward, 2015) indicate the presence of synesthesia, while scores above 2 indicate its absence (Eagleman et al., 2007). Scores falling between these thresholds are interpreted as indicating individuals whose synesthetic status cannot be reliably determined (Eagleman et al., 2007). Such 'indeterminate' scores can arise for a number of reasons, including misunderstandings and false claims, but also because individuals may have inducers that strongly evoke synesthetic experiences without the stability necessary to pass conventional consistency testing (Simner, 2012). This potential dissociation between the consistency and strength of synesthetic associations was recently substantiated in a study showing that consistency, as measured by SB scores, and strength of association, as measured by a congruency index based on the IAT, were uncorrelated and thus are likely to be dissociable elements of synesthetic experience (Lacey et al., 2021). Dissimilarity analysis may be a useful additional way to probe the synesthetic experiences of this 'indeterminate' group. The SB depends on individuals selecting exactly the same color for each grapheme on each trial but, for 'high strength/low consistency' synesthetes, the precise shades of concurrent colors may vary enough to lead to failure on a test of consistency but might not affect dissimilarity analysis. For instance, graphemes evoking varying shades of green and blue would still be closer together as a group, and still separated from graphemes evoking varying shades of red and orange which would themselves still be closer together as a group. Further work is needed to more fully understand the relationship between the perceptual similarities studied here and the strength of synesthetic association; and, indeed, 'indeterminate' synesthesia remains completely unexamined to our knowledge.

Although dissimilarity analysis identified synesthetes and scaled with synesthetic consistency as measured by SB scores, it did not seem to reflect the projector-associator dimension of synesthetic experience We expected that, compared to associator synesthetes, projector synesthetes, who see their concurrent colors in external space and usually co-located with the grapheme, might show a stronger influence of concurrent colors on judgments of grapheme similarity. Contrary to this prediction, grapheme-color RDM correlations were not significantly correlated with PA scores. PA scores have also been shown to be unrelated to SB consistency scores perhaps because the projector/associator subtypes are neither dichotomous nor along a linear continuum (Anderson & Ward, 2015). Thus, grapheme similarity may have been equally salient regardless of how the concurrent was experienced. It is interesting to note, though, that the mean grapheme-color RDM correlation was slightly higher for projectors than associators, in line with our prediction, albeit not significantly so. However, our sample included only four projector synesthetes, reflecting the fact that projectors are less common than associators (Dixon & Smilek, 2005). Since seeing one's synesthetic color projected 'on the page' might be expected to influence the way in which graphemes are sorted for similarity, differences between projectors and associators on this task may bear further investigation in a sample including a larger number of projector synesthetes as a further test of convergent validity.

Finally, an additional benefit of the dissimilarity procedure is that it results in personalized RDMs for graphemes and colors that could be used in functional magnetic resonance imaging (fMRI) studies employing representational similarity analysis (RSA: Kriegeskorte et al., 2008). In the context of fMRI (though RSA has also been applied to neurophysiological data), RSA compares the pair-wise spatial distribution of activation magnitudes across voxels and produces an RDM reflecting the (dis)similarity of these spatial patterns for (dis)similar stimuli. These neural RDMs can then be compared, via second-order correlations, to reference RDMs based on perceptual (dis)similarity or formal computational models in order to test hypotheses about how information is organized in a particular brain region, or about which brain regions organize information that particular way. For example, in the context of grapheme-color synesthesia, we might expect that where synesthetes' grapheme RDMs are more or less influenced by color concurrents (see 'Post-experiment follow-up' above), their second-order correlations to neural RDMs will show a gradient, in the fusiform gyrus, from color-selective areas (for grapheme RDMs strongly influenced by concurrent color) to grapheme-selective areas (for RDMs based predominantly on grapheme shape). Dissimilarity analyses could be carried out quickly and easily, immediately prior to scanning. In addition, they can potentially be extended to other inducer-concurrent combinations.

Potential for using dissimilarity analysis to identify synesthetes

While dissimilarity analysis distinguished synesthetes from non-synesthetes when they had already been classified as such by reference to the consistency of their synesthetic associations as measured by their SB score (Eagleman et al., 2007), an interesting question is whether dissimilarity analysis could be used to identify synesthetes in its own right. This possibility is suggested by the fact that the grapheme-color RDM correlation closely tracked the SB score for synesthetes but not non-synesthetes, and was also much more likely to be individually significant for synesthetes compared to non-synesthetes. This might be useful for kinds of synesthesia that cannot be assessed via the SB, for example, lexical-gustatory synesthesia. Here, one could ask synesthetes to arrange words with specific taste associations and, subsequently, pictures of foodstuffs evoking those tastes (although we acknowledge that taste associations can be complex and need not relate to an identifiable food [Ipser et al., 2020]). To the extent that words with specific taste associations (e.g. bitter or sweet) and, separately, foods with corresponding tastes are grouped together, the resulting RDMs for words and foods should be correlated to some extent. Likewise, dissimilarity analysis might be useful in testing synesthesias involving personality, whether as inducer (as in personality-color synesthesia, see Ramachandran et al., 2012; Simmonds-Moore, 2016) or concurrent (as in sequence-personality synesthesia, see Simner et al., 2011). Another possibility is that dissimilarity analysis could be used as an additional way of checking the synesthetic status of individuals whose SB score falls in the 'indeterminate' range, i.e. individuals whose synesthetic associations are strong but not sufficiently consistent over the short term to pass conventional consistency-based testing (Lacey et al., 2021).

In either case, one issue is how to determine the threshold – an obvious answer is that the inducer-concurrent RDM correlation should be positive and significant but this would only have identified 50% of the synesthetes in the current study. However, this might not be a limitation of dissimilarity analysis *per se* but rather of the fact that we only tested a small subset of synesthetic associations, 8 out of a possible 36 (although testing a subset is not without precedent, see Ásgeirsson et al., 2015). Further work should therefore use the full set of grapheme-color associations with the aim of replicating the present study in terms of distinguishing synesthetes from non-synesthetes and also assessing whether increasing the sample size in this way will detect more individually significant RDM correlations, thus directly testing the potential of dissimilarity analysis as an additional test, whether stand-alone or complementary. It will be important to validate this potential by showing that synesthetic status based on dissimilarity measures separates synesthetes from non-synesthetes on a separate, orthogonal, task. (Note that, in testing the full set of graphemes, it will also be possible to test non-synesthetes on their own associations; this would counter the suggestion that, in being tested on the color associations of their matched synesthete, non-synesthetes were put at a disadvantage: see next section).

Non-random grapheme-color associations for non-synesthetes

Non-synesthetes were tested on the same graphemes and colors as the synesthete to whom they were matched; this increases the likelihood that group differences are due to synesthesia and not stimulus properties (Ásgeirsson et al., 2015). The risk of non-synesthetes creating spurious grapheme-color associations by using mnemonic strategies likely only applies to their completion of the Synesthesia Battery. When completing the grapheme sorting task, participants, whether synesthetes or not, did not know that they would also be asked to sort colors and so non-synesthetes had no reason to strategize colors during the grapheme task. Post-experiment, non-synesthetes reported that, in fact, they chose their SB colors at random and their SB scores show that they could not reproduce these with sufficient consistency on each trial.

However, despite lacking concurrent experiences, non-synesthetes can generate non-random color associations for graphemes in both free- and forced-choice tasks (Simner et al., 2005; note that the SB instructions for non-synesthetes (see 'Synesthesia Battery' above) equate to the free-choice condition in Simner et al., 2005). But, in Simner et al. (2005), participants answered a written questionnaire and only had to generate an association once, non-synesthetes presumably using their imagination while synesthetes used their concurrent experiences. By contrast, in the SB, colors are chosen from a visual display, three times for each grapheme, and the SB score depends on the extent to which the identical color is chosen each time for each grapheme. Here, whether strategizing or not, it is clear that non-synesthetes failed the SB, as they also failed the Test of Genuineness in Simner et al. (2005), including at the individual level (op cit., p1072).

Nonetheless, since non-synesthetes can generate these non-random associations, even if only in the very specific task conditions of Simner et al. (2005), it is worth considering whether it would be worth relinquishing the experimental control afforded by following Ásgeirsson et al. (2015) and testing non-synesthetes on their own grapheme/color associations on the grounds that non-synesthetes might have been disadvantaged by not being given the chance to use their own associations, however inconsistent and fragile. However, firstly, as evidenced by their SB scores, non-synesthetes had no stable color associations, reported choosing colors at random, and could not remember the color choices at the time of the grapheme sorting task. Thus, presenting non-synesthetes with the grapheme/color sets of their matched synesthete was functionally equivalent to, or indistinguishable from, their apparently random and unstable associations. Secondly, even if non-synesthetes could generate stable associations, they would not thereby become synesthetes as they would still lack the vivid concurrent percepts that characterize synesthesia.

Limitations

As this study was conducted online during the COVID-19 pandemic, we could not control the reproducibility of synesthetic colors on the different computer monitors involved in remote testing. Nonetheless, of the 14 synesthetes who responded to a post-experiment follow-up, 12 reported that the colors were a good or reasonable match for their synesthetic associations for the selected graphemes. It is likely that the current results would only be strengthened if, in an in-person replication, we used the same computer and monitor for all participants to ensure the fidelity of on-screen colors to synesthetic colors.

CONCLUSIONS

The present study shows that pair-wise perceptual (dis)similarity quantitatively distinguishes synesthetes from non-synesthetes. This measure scales with scores on the SB (Eagleman et al., 2007), a long-established method of identifying synesthetes, and we speculate that it may also distinguish between projector and associator synesthetes, though further work is necessary to test this hypothesis. Future work should extend the perceptual similarity task to other forms of synesthesia, for example, pitch-color, and the approach may also lend itself to synesthesia types that are more challenging to test, for example, those involving taste or personality associations.

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REFERENCES

Alvarez, B. D., & Robertson, L. C. (2013). The interaction of synesthetic and print color and its relation to visual imagery. *Attention, Perception, & Psychophysics*, 75:1737–1747.

Anderson, H. P., & Ward, J. (2015). Principle component analyses of questionnaires measuring individual differences in synaesthetic phenomenology. *Consciousness & Cognition*, 33:316–324.

Ásgeirsson, Á.G., Nordfang, M. & Sørensen, T.A. (2015). Components of attention in grapheme-color synesthesia: a modeling approach. *PLoS ONE*, 10:e0134456, doi: 10.1371/journal.pone.0134456

Brang, D. & Ahn, E. (2019). Double-blind study of visual imagery in grapheme-color synesthesia. *Cortex*, 117:89-95.

Carmichael, D.A., Down, M.P., Shillcock, R.C., Eagleman, D.M. & Simner, J. (2015). Validating a standardised test battery for synesthesia: does the Synesthesia Battery reliably detect synesthesia? *Consciousness & Cognition*, 33:375-385.

Cohen Kadosh, R. & Henik, A. (2006). Color congruity effect: where do colors and numbers interact in synesthesia? *Cognition*, 42:259-263.

Dixon, M.J. & Smilek, D. (2005). The importance of individual differences in grapheme-color synesthesia. *Neuron*, 45:821-823.

Dixon, M. J., Smilek, D., & Merikle, P. M. (2004). Not all synaesthetes are created equal: Projector versus associator synaesthetes. *Cognitive, Affective, & Behavioral Neuroscience*, 4:335-343.

Eagleman, D. M., Kagan, A. D., Nelson, S. S., Sagaram, D., & Sarma, A. K. (2007). A standardized test battery for the study of synesthesia. *Journal of Neuroscience Methods*, 159:139–145.

Elias, L. J., Saucier, D. M., Hardie, C., & Sarty, G. E. (2003). Dissociating semantic and perceptual components of synaesthesia: Behavioural and functional neuroanatomical investigations. *Cognitive Brain Research*, 16:232–237.

Gaetano, J. (2019). *Welch's t-test for comparing two independent groups: An Excel calculator (1.0.1)*. Retrieved from https://www.researchgate.net/publication/332217175

Ipser, A., Ward, J. & Simner, J. (2020). The MULTISENSE test of lexical-gustatory synaesthesia: an automated diagnostic. *Behavior Research Methods*, 52:544-560.

Kim, C. Y., Blake, R., & Palmeri, T. J. (2006). Perceptual interaction between real and synesthetic colors. *Cortex*, 42:195–203.

Kriegeskorte, N., & Mur, M. (2012). Inverse MDS: Inferring dissimilarity structure from multiple item arrangements. *Frontiers in Psychology*, 3:245, doi:10.3389/fpsyg.2012.00245

Kriegeskorte, N. Mur, M. & Bandettini, P. (2008). Representational similarity analysis – connecting the branches of systems neuroscience. *Frontiers in Systems Neuroscience*, 2:4, doi: 10.3389/neuro.06.005.2008

Lacey, S., Jamal, Y., List, S.M., McCormick, K., Sathian, K. & Nygaard, L.C. (2020). Stimulus parameters underlying sound-symbolic mapping of auditory pseudowords to visual shapes. *Cognitive Science*, 44:e12883.

Lacey, S., Martinez, M.O., McCormick, K. & Sathian, K. (2016). Synesthesia strengthens sound-symbolic cross-modal correspondences. *European Journal of Neuroscience*, 44:2716-2721.

Lacey, S., Martinez, M., Steiner, N. Nygaard, L.C. & Sathian, K. (2021). Consistency and strength of grapheme-color associations are separable aspects of synesthetic experience. *Consciousness & Cognition*, 91:103137.

Lenhard, W. & Lenhard, A. (2016). Calculation of Effect Sizes. Retrieved from https://www.psychometrica.de/effect_seize.html, *Psychometrica* doi: 10.13140/RG.2.2.17823.9329.

Lupiáñez, J., & Callejas, A. (2006). Automatic perception and synaesthesia: Evidence from colour and photism naming in a Stroop-negative priming task. *Cortex*, 42:204–212.

Majewska, O., McCarthy, D., van den Bosch, J., Kriegeskorte, N., Vulic, I., & Korhonen, A. (2020). Spatial multi-arrangement for clustering and multi-way similarity dataset construction. *LREC 2020 - 12th International Conference on Language Resources and Evaluation, Conference Proceedings*, 5749–5758.

Mattingley, J. B., Rich, A. N., Yelland, G., & Bradshaw, J. L. (2001). Unconscious priming eliminates automatic binding of colour and alphanumeric form in synaesthesia. *Nature*, 410:580–582.

Novich, S., Cheng, S. & Eagleman, D.M. (2011). Is synaesthesia one condition or many? A large-scale analysis reveals subgroups. *Journal of Neuropsychology*, 5:353-371.

Ramachandran, V.S. & Hubbard, E.M. (2001a). Psychophysical investigations into the neural basis of synaesthesia. *Proceedings of the Royal Society of London B*, 268:979-983.

Ramachandran, V.S. & Hubbard, E.M. (2001b). Synaesthesia – A window into perception, thought, and language. *Journal of Consciousness Studies*, 8:3-34.

Ramachandran, V.S., Miller, L., Livingstone, M.S. & Brang, D. (2012). Colored halos around faces and emotion-evoked colors: A new form of synesthesia. *NeuroCase*, 18:352-358.

Rich, A.N. & Karstoft, K.-I. (2013). Exploring the benefit of synaesthetic colours: testing for “pop-out” in individuals with grapheme-color synaesthesia. *Cognitive Neuropsychology*, 30: 110-125.

Rothen, N., Seth, A. K., Witzel, C., & Ward, J. (2013). Diagnosing synaesthesia with online colour pickers: Maximising sensitivity and specificity. *Journal of Neuroscience Methods*, 215:156–160.

Rouw, R. & Scholte, H.S. (2007). Increased structural connectivity in grapheme-color synesthesia. *Nature Neuroscience*, 10:792-797.

Simmonds-Moore, C.A. (2016). An interpretative phenomenological analysis exploring synesthesia as an exceptional experience: insights for consciousness and cognition. *Qualitative Research in Psychology*, 13:303-327.

Simner, J. (2012). Defining synaesthesia. *British Journal of Psychology*, 103:1–15.

Simner, J., Gärtner, O. & Taylor, M.D. (2011). Cross-modal personality attributions in synaesthetes and non-synaesthetes. *Journal of Neuropsychology*, 5:283-301.

Simner, J., Ward, J., Lanz, M., Jansari, A., Noonan, K. et al. (2005). Non-random associations of graphemes to colours in synaesthetic and non-synaesthetic populations. *Cognitive Neuropsychology*, 22:1069-1085.

Stroop, J.R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18:643-662.

Ward, J. (2013). Synesthesia. *Annual Review of Psychology*, 64:49-75.

Ward, J., Hovard, P., Jones, A. & Rothen, N. (2013). Enhanced recognition memory in grapheme-color synaesthesia for different categories of visual stimuli. *Frontiers in Psychology*, 4:762, doi: 10.3389/fpsyg.2013.00762

Ward, J., Li, R., Salih, S., & Sagiv, N. (2007). Varieties of grapheme-colour synaesthesia: A new theory of phenomenological and behavioural differences. *Consciousness & Cognition*, 16:913–931.

a

b

0	**.17**	**.06**	**.18**	**.17**	**.21**	**.07**	**.22**
.17	0	**.19**	**.26**	**.23**	**.22**	**.12**	**.15**
.06	.19	0	**.19**	**.13**	**.25**	**.13**	**.22**
.18	.26	.19	0	**.09**	**.15**	**.24**	**.2**
.17	.23	.13	.09	0	**.2**	**.19**	**.19**
.21	.22	.25	.15	.2	0	**.25**	**.18**
.07	.12	.13	.24	.19	.25	0	**.2**
.22	.15	.22	.2	.19	.18	.2	0

0	**.12**	**.06**	**.18**	**.21**	**.18**	**.07**	**.19**
.12	0	**.19**	**.25**	**.2**	**.23**	**.11**	**.15**
.06	.19	0	**.18**	**.26**	**.21**	**.1**	**.26**
.18	.25	.18	0	**.2**	**.11**	**.21**	**.25**
.21	.2	.26	.2	0	**.14**	**.25**	**.12**
.18	.23	.21	.11	.14	0	**.25**	**.16**
.07	.11	.1	.21	.25	.25	0	**.2**
.19	.15	.26	.25	.12	.16	.2	0

c

Grapheme vector: .17, .06, .18, .17, .21, .07, .22, .19, .26, .23 [...] .25, .18, .2

Color vector: .12, .06, .18, .21, .18, .07, .19, .19, .25, .2 [...] .25, .16, .2

Correlation

Figure 1: Perceptual similarity task. (a) Over multiple trials, participants arranged first graphemes, and then colors, according to how similar they looked; similar items were placed close together and dissimilar items further apart. (b) The distances obtained in (a) were used to create a representational dissimilarity matrix (RDM) of the pair-wise dissimilarity between items. (c) Since the RDMs are symmetric across the diagonal, we used one half of the off-diagonal data; these data were vectorized row-by-row for graphemes and colors, and the correlation of these two vectors quantifies the relationship between the grapheme and color RDMs.

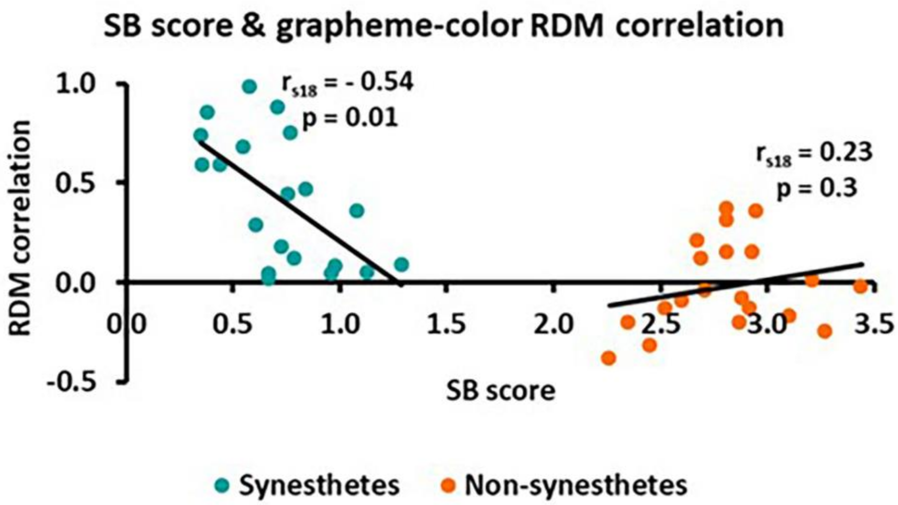

Figure 2: Synesthetes' SB scores were significantly associated with their grapheme-color RDM correlation values, indicating that the influence of synesthetic color experiences on grapheme similarity increased with increasing consistency of synesthetic color associations. By contrast, non-synesthetes' SB scores and grapheme-color RDM correlation values were non-significantly associated.

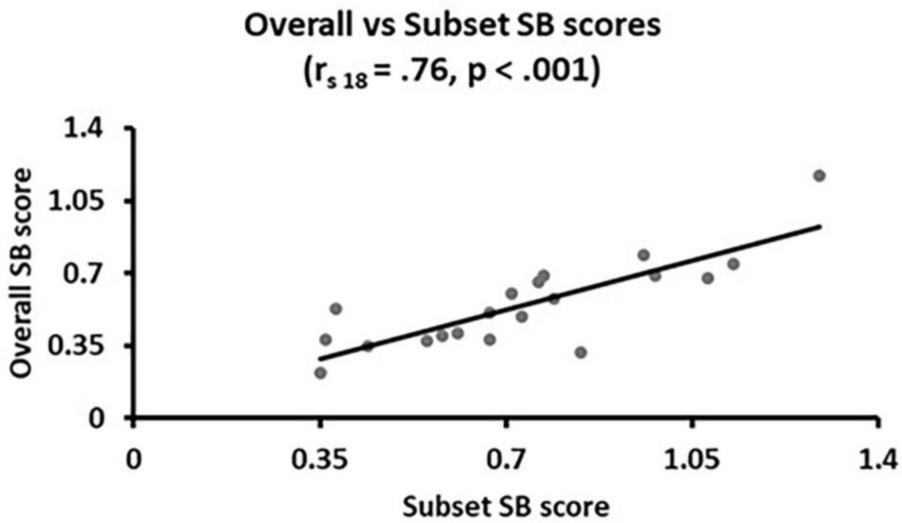

Figure 3: Synesthetes' overall SB scores for the complete set of graphemes for which they experienced concurrent colors were significantly correlated with the SB score calculated for the subset of eight graphemes on which they were tested.