UNIVERSITY OF AMSTERDAM

UvA-DARE (Digital Academic Repository)

Distinct colours in the 'synaesthetic colour palette'

Rouw, R.; Root, N.B.

DOI
10.1098/rstb.2019.0028

Publication date
2019

Document Version
Final published version

Published in
Philosophical Transactions of the Royal Society B - Biological Sciences

License
Article 25fa Dutch Copyright Act (https://www.openaccess.nl/en/policies/open-access-in-dutch-copyright-law-taverne-amendment)

Link to publication

Citation for published version (APA):
Rouw, R., & Root, N. B. (2019). Distinct colours in the 'synaesthetic colour palette'. *Philosophical Transactions of the Royal Society B - Biological Sciences*, *374*(1787), Article 20190028. https://doi.org/10.1098/rstb.2019.0028

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, P.O. Box 19185, 1000 GD Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)

Download date:15 Sept 2026

PHILOSOPHICAL TRANSACTIONS B

royalsocietypublishing.org/journal/rstb

Research

Cite this article: Rouw R, Root NB. 2019 Distinct colours in the 'synaesthetic colour palette'. *Phil. Trans. R. Soc. B* **374**: 20190028.
http://dx.doi.org/10.1098/rstb.2019.0028

Accepted: 17 July 2019

One contribution of 16 to a discussion meeting issue 'Bridging senses: novel insights from synaesthesia'.

Subject Areas:
behaviour, cognition, neuroscience

Keywords:
synaesthesia, colour perception, cross-modal associations

Author for correspondence:
Romke Rouw
e-mail: r.rouw@uva.nl

Electronic supplementary material is available online at https://doi.org/10.6084/m9.figshare.c.4666226.

THE ROYAL SOCIETY PUBLISHING

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

Distinct colours in the 'synaesthetic colour palette'

Romke Rouw[1] and Nicholas B. Root[2]

[1]Brain and Cognition, Psychology Department, University of Amsterdam, Nieuwe Achtergracht 129-B, 1018 WT Amsterdam, The Netherlands
[2]Department of Psychology, University of California San Diego, 9500 Gilman Drive, San Diego, CA 92093-0109, USA

RR, 0000-0001-9697-5360; NBR, 0000-0002-8521-3253

In grapheme-colour synaesthesia, particular linguistic elements evoke particular colour sensations. Interestingly, when asked, non-synaesthetes can also associate colours to letters, and previous studies show that specific letter-to-colour associations have similar biases to those of synaesthetes. However, it is an open question whether the colours reported by synaesthetes and non-synaesthetes differ *overall*: is there a 'synaesthetic colour palette'? In this study, we visualize the overall distribution in colour space of colour concurrents in grapheme-colour synaesthetes, and colour associations in non-synaesthetic controls. We confirm the existence of a synaesthetic colour palette: colour concurrents in synaesthetes are different from colour associations in non-synaesthetes. We quantify three factors that distinguish the colour palette of synaesthetes and non-synaesthetes: synaesthetes have an increased over-representation of 'pure' (unmixed) hues, an increased presence of 'warm' (yellow, orange, brown) colours, and an increased presence of achromatic (grey, white, black) colours. Furthermore, we demonstrate that differences in the synaesthetic colour palette can be used to train a machine learning algorithm to reliably classify single subjects as synaesthetes versus non-synaesthetes without using test–retest consistency data. As far as we know, this is the first time an individual could be 'diagnosed' as a synaesthete, based only on his or her colours evoked by letters.

This article is part of a discussion meeting issue 'Bridging senses: novel insights from synaesthesia'.

1. Introduction

Synaesthesia is a neurodevelopmental condition in which a particular percept or concept (inducer) evokes a seemingly unrelated perceptual experience (concurrent). Historically, synaesthesia was considered a rare, idiosyncratic and bizarre condition [1], but in the past two decades a renewed interest in synaesthesia has revealed objectively measurable and reproducible characteristics that established synaesthesia as a 'real' condition (e.g. [2]; for a review, see [3]). Thanks to this pioneering work, the research field currently concurs on a set of defining characteristics of synaesthesia: synaesthetes experience specific and consistent pairings across different types of sensations (or experiences), and these experiences are conscious, percept-like, and of an automatic, involuntary and effortless nature (e.g. [4–9]).

Of these characteristics, the specificity and consistency of the inducer-to-concurrent pairings is the feature most commonly used to decide who is, and who is not, to be included as synaesthete in a scientific exploration. Inducer–concurrent pairings can be stable over months or even years [10], and the specificity and consistency of these pairings is considered to be the 'gold standard' or 'Test of Genuineness' for synaesthetes to be included in scientific studies. A well-known example is the online Eagleman synaesthesia battery [11], in which inducer–concurrent pairings are repeatedly measured, and only individuals whose responses are consistent across repeats are considered to be synaesthetes.

© 2019 The Author(s) Published by the Royal Society. All rights reserved.

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

In the most-studied (and relatively common) type of synaesthesia, a particular linguistic element (e.g. the letter 'R') evokes a colour association (e.g. sky blue). Although the specific grapheme-to-colour mappings of any two synaesthetes often appear idiosyncratic, research using large samples of synaesthetes has revealed general biases in the pattern of associations [12,13]. A diverse range of factors have been shown to bias the distribution of concurrent colours for inducing graphemes: the colour of graphemes can be influenced by shape [14,15], sound [16,17], frequency of occurrence [12,18], meaning [13,19] and even innate colour-shape preferences [20]. Some studies also found evidence that a specific memory of an environmental influence, such as coloured refrigerator magnets, can influence the concurrent colours experienced for particular graphemes [21,22].

Critically, many of the biases that influence inducer–concurrent relationships in synaesthetes also influence grapheme-colour associations in non-synaesthetes who are forced to choose colours for letters. This is remarkable, given that these non-synaesthetes do not experience colours with letters and therefore feel as if they are 'randomly' choosing colours (e.g. [12,23]). For example, both synaesthetes and non-synaesthetes are influenced by colour names: the letter Y tends to be yellow, the letter B tends to be blue and so on [12]. In addition, both synaesthetes and non-synaesthetes are influenced by 'index words' [24]: if a word that is commonly associated with a letter (e.g. 'D is for dog'), has a prototypical colour association (dogs are brown), this can influence the colour of that letter (D is brown). Furthermore, the first letter of the synaesthete's language is associated with red in many of the world's languages, for both synaesthetes and non-synaesthetes ([23,25], but see [26]). Finally, the phonetic properties of letters influence colour associations in both synaesthetes and non-synaesthetes [27–34]; for example, 'lower' or 'back' acoustic vowel characteristics (e.g. in an [u]), are darker, redder and bluer, whereas 'higher' or 'front' vowel characteristics (e.g. in [i]), are lighter, greener and yellower. Cuskley *et al*. [35] replicated these findings with a large sample size, and furthermore showed that letter category (a particular vowel) is a better predictor of colour than the acoustic measures, thus also showing a role of categorical (letter) perception.

The studies on colour concurrents in synaesthetes, versus colour associations in non-synaesthetes, have presented us with a paradox. On the one hand, the presence of a consistent and specific mapping from letter-to-colour is a key characteristic of synaesthesia, and is even used as the most important screening tool in synaesthesia studies. On the other hand, non-synaesthetes forced to generate letter–colour associations show biases that are similar to those of synaesthetes. The existence of these cross-modal associations in non-synaesthetes has led to a debate in the field about the degree to which synaesthesia is 'special', or whether it is an 'extreme case' of typical cross-modal cognition [36–38].

Here, we address this debate using a novel approach. Previous studies have shown several factors that influence the synaesthetic colours evoked by specific letters. There are, however, many possible (known and unknown) factors driving synaesthetic colour concurrents. We examine the range of colours evoked by all letters, viewing the colours themselves as the representational system reflecting all influences of (letter) properties evoking these colours.

Hamada *et al*. [39] were the first to examine the overall distribution of synaesthetes' colours in colour space: they examined over 5000 colour associations using different sets of graphemes (Kanji, Hiragana, Katakana, Latin letters and Arabic numerals) in eight synaesthetes. The synaesthetic colour distribution in an a^*b^* chromaticity space showed that the colour associations showed multiple clusters, rather than a random or uniform distribution. Furthermore, categorizing all colours in one of five Munsell colours (yellow, green, blue, purple, red) showed that similarly shaped characters in Kanji and Katakana had similar colours, and that the most frequent colour was yellow.

Hamada *et al*.'s study convincingly demonstrates that synaesthetes have non-uniform, non-random patterns of colour associations, but it leaves open the question whether non-synaesthetes—when forced to choose colours for letters—have a similar pattern of colour associations. In other words, is the clustered distribution caused by general biases (e.g. certain colours are more prominently present in our cognitive system, or some colours are more easily generated) or does it reveal patterns that are unique to synaesthetes? As far as we know, no study has ever examined the degree to which the overall distribution of synaesthetic colour concurrents is similar to (or different from) the overall distribution of non-synaesthetic colour associations.

In this study, we first visualize all colours evoked by letters in a group of grapheme-colour synaesthetes, as well as all colours associated with these letters in a group of non-synaesthete controls. We next determine whether the distribution of synaesthetic colour concurrents is quantitatively different from the distribution of non-synaesthetic colour associations. Finally, we explore whether an individual's reported colour associations can be used to predict whether that individual is a synaesthete (without consistency data). In other words, is there a synaesthetic colour 'palette'?

2. Experiments

(a) Subjects

English- and Dutch-speaking subjects were from a previously collected database [40] of grapheme-colour associations. English-speaking subjects were recruited through fliers posted on the University of California, San Diego campus, as well as similar ads on the web. Dutch-speaking subjects were recruited through various means, including from the general public (via television or radio interviews) as well as students at the University of Amsterdam. A total of 138 English-speaking and 202 Dutch-speaking subjects contributed to this study.

All subjects took the Eagleman Synesthesia Battery [11], and provided letter–colour associations for each letter three times (i.e. 78 trials total). Subjects were told that their task was to pick the 'best' colour for each letter, but that they should 'not think too hard': they should 'pick the colour that first comes to mind when you think of the letter'. In the present experiment, we classified subjects as synaesthetic or non-synaesthetic using the recommendations of Rothen *et al*. [41]: the test–retest consistency of a letter is defined as the sum of the Euclidean distance in CIELUV colour space between the colours reported for each of the three repeated measurements of each grapheme-colour association; a subject is classified as a synaesthete if the average test–retest consistency is less than 135. Our dataset contained 78 English-speaking synaesthetes, 162 Dutch-speaking synaesthetes, 60 English-speaking non-synaesthetes and 40 Dutch-speaking non-synaesthetes.

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

From this initial dataset, we excluded subjects who did not report a colour for at least 50% of the letters (which can lead to inflated estimates of test–retest consistency; 17 English- and 39 Dutch-speaking subjects excluded), and also excluded subjects who chose black on more than 80% of trials (suggesting they misunderstood the task, and chose the printed letter colour; seven English-speaking subjects excluded). Finally, we excluded four English-speaking subjects who admitted using memorization tricks to artificially increase their consistency score (rather than providing their natural associations). Our final dataset contained 54 English-speaking synaesthetes, 126 Dutch-speaking synaesthetes, 56 English-speaking non-synaesthetes and 37 Dutch-speaking non-synaesthetes.

Finally, from this dataset, we removed all but the first trial for each letter. In most studies of synaesthetic associations, the three trials for each letter are averaged, but this approach is problematic for our research question, because it yields colours that were never actually chosen by a participant, hindering inspection of their exact colour choices. Furthermore, it would confound the comparison between the synaesthetic and non-synaesthetic palette, as non-synaesthetes' associations are necessarily more inconsistent across repetitions, and therefore more strongly affected by the averaging procedure. For example, if a non-synaesthete would chose red, green and blue across three trials of one letter, the averaged colour in CIELUV colour space is white, which is not a reasonable representation of the true data. Therefore, we need to choose one of the three responses, and reasoned that in non-synaesthetes the first response was least likely to be confounded by other responses. Furthermore, removing all but the first trial is essentially equivalent to measuring each letter–colour association once. This procedure is thus in line with the overall question in this project: can reported colour associations in an individual be used to predict if that individual is a synaesthete, without using consistency data?

(b) Experiment 1: visualizing and quantifying the synaesthetic 'palette'

In this experiment, we visualize the colours evoked by letters; in particular, their distribution in colour space. A perfectly random palette would produce a uniform distribution of colours in colour space, whereas biases in the colours synaesthetes or non-synaesthetes associate with letters would produce an inhomogeneous palette. The palettes of synaesthetes and non-synaesthetes will furthermore be compared, to determine whether there is a significant difference in the synaesthetic 'colour palette'.

(i) Methods

*CIELUV u*v* visualizations.* For our first visualizations (figure 1*a*,*b*), we randomly sampled 1500 associations from each group (synaesthetes versus non-synaesthetes), and plotted them in the *u*v** plane of CIELUV colour space. This colour space was designed (using human perceptual measurements) to be perceptually uniform: pairs of colours which are equidistant in CIELUV space are approximately equal in perceived colour difference. We used the CIELUV space because measures of synaesthetic colour consistency in CIELUV are most consistent (of any colour space) with subjects' subjective reports [41]. Figure 1*c* depicts 1500 randomly generated points in CIELUV colour space; i.e. a distribution of colours that could be expected if there were no systematic biases in the synaesthetic or non-synaesthetic palette. For our next visualizations (figure 1*d*,*e*), we plotted the histograms of the frequency of all synaesthete and non-synaesthete colour associations as a function of the hue angle, arctan2(*v**,*u**). These figures omit the saturation and luminance of the colour associations, and instead indicate only whether associations are biased towards certain hue angles.

Berlin–Kay colour category visualizations. For our final visualizations (figure 1*f*,*g*,*h*), we consider the colour *category* of the letter–colour associations, rather than the actual colour. Semantic associations with colour names demonstrably influence some grapheme-colour associations (e.g. 'B for Blue', [12]), suggesting that biases may arise at the level of colour categories rather than particular locations in colour space. We chose a categorization that most closely fits with basic colour terms as obtained across different cultures: the Berlin–Kay basic colour terms [42]. For our participant groups (Dutch and American), this entails 11 basic colour terms: black, white, red, green, yellow, blue, brown, purple, pink, orange and grey. Each letter–colour association (for both synaesthetes and non-synaesthetes) in our data was categorized into these 11 basic colours [42], using a previously collected dataset of 1354 colours that had been categorized into basic colour terms [42] by 1177 subjects [43]. For each colour in our dataset, we found the closest colour (i.e. shortest Euclidean distance in CIELUV) in Jraisatti & Douven's dataset [43], and then used this to assign to our colour the likeliest Berlin–Kay colour term (the modal Berlin–Kay term for the colour in the Jraisatti & Douven database).

(ii) Results

Qualitative observations. In all three visualizations (*u*v** plane, hue angle, colour category), both synaesthetes' and non-synaesthetes' palette appears different from what would be expected under a uniform distribution (i.e. choosing colours randomly). First, the (*u*v** plane and hue angle) visualizations show red, green, blue and—to a lesser degree—yellow, 'axes' or 'peaks'. This shows that a few specific colour hues are more common for both synaesthetes and non-synaesthetes. Furthermore, colour regions also show a non-uniform distribution; in particular, more synaesthetic colours are in the yellow-to-red range than in the purple-to-green area. Note that this is entirely consistent with the high density of 'yellow' Munsell colours (compared to red, green, blue and purple) reported for the synaesthetes in Hamada *et al.* [39]. In addition, the Berlin–Kay colour category visualizations show clear differences between synaesthetes and non-synaesthetes in terms of the presence of colour categories. The follow-up quantitative analyses were set up to show exactly which colour categories are significantly different between the two participant groups.

Quantitative analyses. We first examined non-uniform distribution of colour hues. The four distinct sharp peaks/axes in figure 1*a*,*b*,*d*,*e* were found at the hue angles for 'unique' hues (shades of red, green, blue and yellow that are 'pure'—not mixtures of two or more colours). Analyses showed that indeed 15.4% of all chromatic colour associations for non-synaesthetes, and 18.5% for synaesthetes, are within one degree of the hue angle of a unique hue (significantly more than the 2.2% that would be expected by chance; binomial test; synaesthetes: $p < 0.0001$, $RR = 8.32$; non-synaesthetes: $p < 0.0001$, $RR = 6.92$). Consistent with our qualitative observations, synaesthetes

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

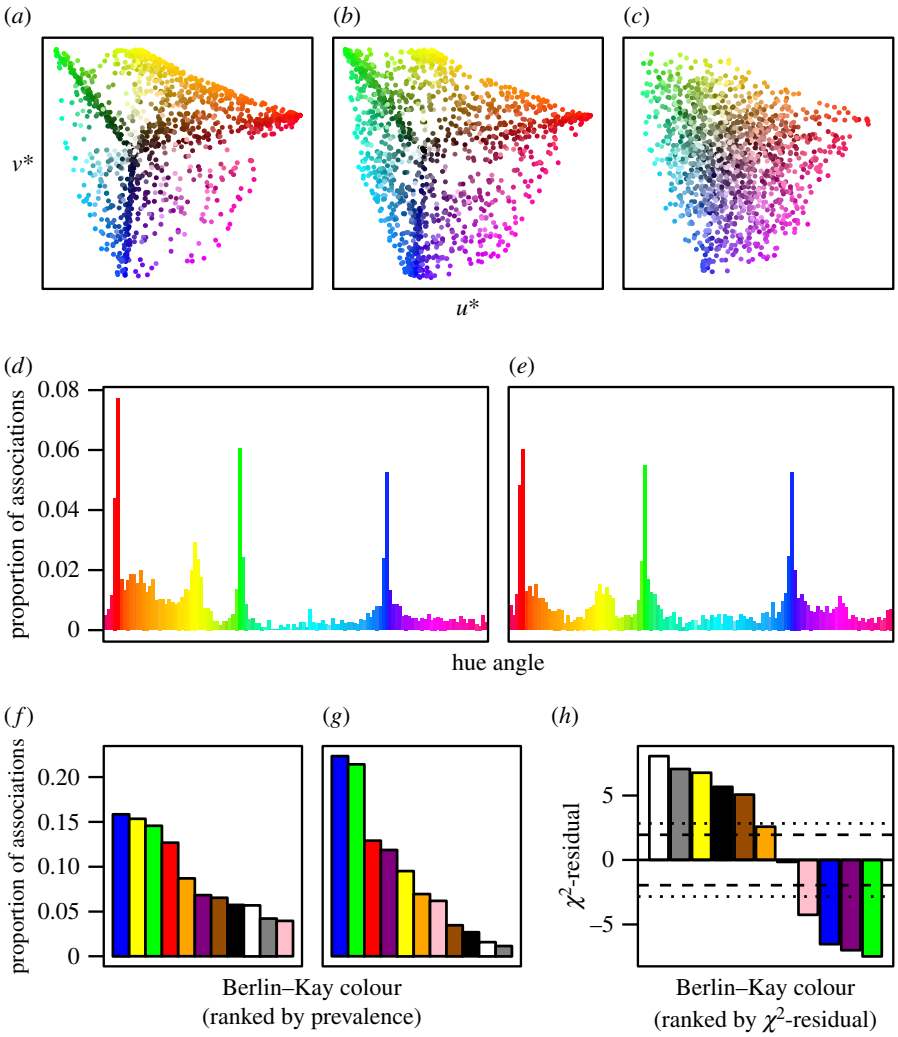

Figure 1. Visualizations of the synaesthetic and non-synaesthetic 'palette'. (*a–c*) The distribution in the *u***v** plane of CIELUV colour space of equal-size random samples from (*a*) synaesthetes, (*b*) non-synaesthetes and (*c*) a uniform distribution in CIELUV. Each graph contains the same number of points. (*d*,*e*) The distribution in hue angle of CIELUV of all chromatic associations of (*d*) synaesthetes and (*e*) non-synaesthetes. A uniform distribution in this space would be a 'flat' histogram. (*f*,*g*) The distribution of associations in each Berlin–Kay colour category for (*f*) synaesthetes and (*g*) non-synaesthetes. (*h*) The standardized residuals of a χ^2-test of independence for the distribution of Berlin–Kay colour associations for synaesthetes versus non-synaesthetes. The large dashed lines are uncorrected $p < 0.05$ thresholds for significance; the small dashed lines are Bonferroni-corrected $p < 0.05$ thresholds.

experienced 3.1% more associations in this range (within 1° of a unique hue) than non-synaesthetes, a statistically significant difference ($\chi^2_1 = 8.92$, $p < 0.005$, $RR = 1.20$).

Next, we determined whether the distribution of Berlin–Kay colour categories is quantitatively different in synaesthetes as compared with non-synaesthetes. We ran a 2×11 χ^2-test of the null hypothesis that the counts of colours in each category for synaesthetes and non-synaesthetes came from the same distribution. The χ^2-test showed a highly significant difference between synaesthetic and non-synaesthetic distribution in Berlin–Kay colour categories ($\chi^2_{10} = 354.11$, $p < 0.0001$). This result confirms that synaesthetic colour concurrents are different from non-synaesthetic colour associations. Figure 1*h* depicts the standardized χ^2-residual [44] for each colour (positive values mean that the association is likelier in synaesthetes, while associations with negative values are likelier in non-synaesthetes). These residuals are approximately normally distributed, and can be used as a moderately conservative post-hoc test [45] to determine which colour(s) significantly contributed to the overall χ^2-value. The dashed lines depict cut-off points for the $p < 0.05$ threshold, either uncorrected (large dash) or Bonferroni-corrected for 11 comparisons (small dash). The colour categories are not equally present in both groups. First, synaesthetes are significantly likelier than non-synaesthetes to experience the achromatic colours black, white and grey. Second, synaesthetes are significantly likelier to experience yellow, brown and (marginally significant) orange, whereas non-synaesthetes are significantly likelier to experience green, purple, blue and pink. Interestingly, this distinction neatly fits a relative preference for 'warm' colour in synaesthetes and 'cool' colours in non-synaesthetes. The only exception is that the colour red is equally present in non-synaesthetes and synaesthetes.

(iii) Conclusion

Visualization of all colours chosen by synaesthetes reveals the *synaesthetic palette*: an inhomogeneous distribution of colours in perceptually uniform colour space. Both qualitative and quantitative analyses suggest that (i) synaesthetic and non-synaesthetic palettes are non-uniform in colour space and (ii) synaesthetic and non-synaesthetic palettes are different from each other. We quantified the differences between the synaesthetic and non-synaesthetic palette, and found that synaesthetes are more likely to experience 'unique' hues (pure red, green, blue or yellow), achromatic colours (black, white, grey), and 'warm' colours (yellow, brown, orange),

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

whereas non-synaesthetes are more likely to experience 'cool' colours (green, pink, blue, purple).

(c) Experiment 2: classifying synaesthesia status based on an individual's colour palette

Although we have observed strong differences at the group level between synaesthetes and non-synaesthetes, these measures communicated information about the size of the effect in the *population*, rather than in the *individual*. Can the observed differences between synaesthetic and non-synaesthetic colour associations be used to reliably identify a single subject as a synaesthete or a non-synaesthete, without knowing anything other than the subject's reported colours (e.g. no consistency data)? In other words, can the synaesthetic 'palette' be used to classify a subject as a synaesthete or non-synaesthete?

(i) Methods

We used leave-one-out cross-validation to quantify the accuracy of a Naive Bayes classifier (using the *naive Bayes* function in R's *e1071* package; [46]) trained to classify synaesthesia status using only the subject's colours (the subject's proportion of associations for each Berlin–Kay colour, e.g. 20% red, 6% blue, etc.). Naive Bayes classifiers compute the conditional probability of feature values (in this case, proportion of associations for each Berlin–Kay colour) for each target class (in this case, synaesthete or non-synaesthete). Given a new set of feature values (i.e. a new subject), the classifier then uses Bayes' Rule to predict the probability of class membership, given the observed values. Leave-one-out cross-validation is a general machine learning technique used to combat overfitting: for each subject, the classifier is trained using data from which the subject to be classified has been removed. In this way, each subject's synaesthesia status was predicted from just the colours of their palette, using a classifier that was not trained on that subject's data.

Classification accuracy is the leave-one-out cross-validation accuracy at the optimal decision boundary. Since we wish to weight false negatives and false positives equally, our optimal decision boundary is Youden's J [47], the point which maximizes the distance between the ROC (receiver operating characteristic) curve and the diagonal; i.e. the point which maximizes both sensitivity and specificity. AUC (area under the ROC curve) is a measure of performance across *all* choices of threshold; the AUC value can be interpreted as the probability that the classifier assigns a higher probability of synaesthesia to a randomly chosen synaesthete than to a randomly chosen non-synaesthete.

(ii) Results

The classifier that was trained using leave-one-out cross-validation yielded a classification accuracy of 77.7% at the Youden's J threshold, with a sensitivity of 81.7%, and specificity of 69.9%. The AUC was significantly higher than chance (Mann–Whitney test, $p < 0.0001$, 95%). Table 1 gives full performance measures of the classifier. Evidently, the difference between the synaesthetic and non-synaesthetic palette (figure 1) is sufficient to classify synaesthetes versus non-synaesthetes at the level of a single individual.

In addition to testing generalizability using leave-one-out cross-validation, we also tested generalizability by subsetting our data into Dutch and English samples. We calculated both within-language classification accuracy (using leave-one-out cross-validation) and cross-language classification accuracy: could a classifier trained on only Dutch data correctly classify English synaesthetes, and vice versa? Table 2 gives the performance measures for these classifiers; figure 2 depicts the ROC curve for each classifier. Classification accuracy was remarkably high for all iterations (all AUCs significant at $p < 0.0001$).

Table 1. Performance measures of the Naive Bayes classifier trained to predict a subject's synaesthesia status using only the distribution of Berlin–Kay colour categories in the palette.

accuracy	sensitivity	specificity	AUC	AUC 95% CI
0.777	0.817	0.699	0.833	[0.783, 0.882]

(iii) Conclusion

The high performance of the classifier suggests that even at the level of an individual subject there is a meaningful difference between grapheme-to-colour mappings for synaesthetes and non-synaesthetes. Together, the results show that the set of colours an individual has provided is sufficient to predict with approximately 78% accuracy if that individual will qualify as a synaesthete on the Eagleman Battery [11].

(d) Experiment 3: testing (alternative) explanations for the synaesthetic palette

Having shown that there are significant differences in the colour palette of synaesthetes and non-synaesthetes, we next sought to explore the potential mechanisms of this difference. In particular, we wanted to rule out three potential confounds that might cause us to observe a difference in the synaesthetic 'palette' when none was actually present.

(e) Experiment 3A: do particular grapheme-colour associations drive the observed differences between synaesthetes and non-synaesthetes?

Previous research has shown that for both synaesthetes and non-synaesthetes there are biases in the *particular* colour associated with a *particular* grapheme [12]. A possible confound in our findings could be that a few very strong (consistent) letter–colour associations that are present in synaesthetes but not non-synaesthetes (or vice versa) make the overall synaesthetic 'palette' appear different. Is the obtained difference in palette attributable to the outsized influence of just a few letters?

(i) Method and results

To rule out the potential confound of only a few strong letter-colour associations driving the effect, we replicated the χ^2-residual analysis from Experiment 1, but ran 26 χ^2-tests (one for each letter) instead of a single test for all letters. For 10 out of 26 letters (indicated with asterisks next to the letter in figure 3*a*), there was a significant difference in the colour associations of synaesthetes and non-synaesthetes (omnibus χ^2-statistic; $p < 0.05$, Bonferroni-corrected for 26 comparisons). For each of these 10 letters, the colours which significantly

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

Table 2. Within- and between-language performance measures of the Naive Bayes classifier, trained to predict a subject's synaesthesia status using only the distribution of Berlin–Kay colour categories in the palette.

train	test	accuracy	sensitivity	specificity	AUC	AUC 95% CI
English	English	0.800	0.815	0.786	0.871	[0.806, 0.935]
Dutch	Dutch	0.748	0.730	0.811	0.835	[0.769, 0.902]
Dutch	English	0.755	0.778	0.732	0.825	[0.749, 0.901]
English	Dutch	0.736	0.738	0.730	0.802	[0.725, 0.879]

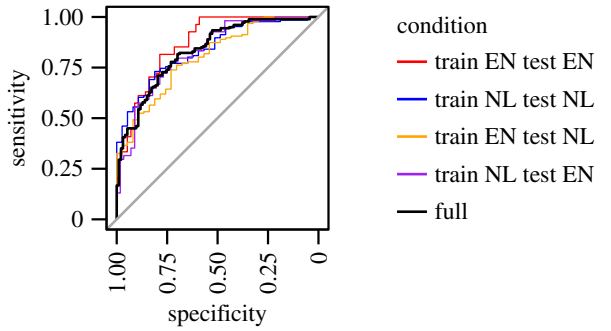

Figure 2. The ROC curve of the classifiers. Sensitivity is the probability of correct classification for synaesthetes; specificity is the probability of correct classification for non-synaesthetes. EN, English; NL, Dutch.

contribute to the omnibus χ^2-statistic (indicated with the larger circles in figure 3*a*) are consistent with differences in the synaesthetic palette. Visualizing the data as a function of colour (figure 3*b*) clearly shows that the difference between the synaesthetic and non-synaesthetic palettes ('warm' versus 'cool', achromatic versus chromatic) is not driven exclusively by these 10 large (significant) effects. For example, for 25/26 letters, white is more common in synaesthetes than non-synaesthetes, which suggests that the tendency for synaesthetes to experience more white graphemes cannot be attributed to just the large residuals for 'I' and 'O'. To quantify this observation, we removed these 10 letters and re-ran the χ^2-test from Experiment 1 (depicted in figure 1*h*) using only the 16 letters for which there was no per-letter significant difference in the synaesthetic palette (as compared with non-synaesthetic). Figure 3*c* depicts the residuals of this χ^2-test; it is clear that the effects described in Experiment 1 (synaesthetes experience more achromatic colours, more 'warm' colours and fewer 'cool' colours) are still present even after removing the letters which most strongly differentiate synaesthetes from non-synaesthetes.

(ii) Conclusion

In sum, our analyses showed that the observed differences between the synaesthetic and non-synaesthetic palette cannot be attributed to *particular* grapheme-colour associations; instead, the difference appears to be present in associations across most graphemes.

(f) Experiment 3B: did misinterpretation of instructions cause the observed differences between synaesthetes and non-synaesthetes?

Synaesthetes had more achromatic (black/grey/white) colours in their palette. One important potential confound in this result is that perhaps non-synaesthetes did not understand the task instructions, and did not think that they were allowed to choose an achromatic colour. Indeed, 46.2% of non-synaesthetes did not report a single achromatic association, as would be expected if they interpreted 'colour' to mean chromatic colours only. To control for this potential confound, we collected data from a new set of non-synaesthetes and explicitly instructed them that they were allowed to choose black, white and grey as 'colours'.

(i) Methods and results

Subjects were 88 non-synaesthetes recruited from the University of California San Diego. Methods were identical to Experiment 1, except that we added to the task instructions the sentence 'In this experiment, white, grey and black are considered 'colours'; you can also choose each of these if you think it is the best colour for that letter'. Data were pre-processed exactly as in Experiment 1: non-synaesthete status was verified (average sum of the Euclidean distance in CIELUV between repetitions greater than 135), and all but the first trial for each letter was removed. Each colour choice was categorized into Berlin–Kay colours using the same method as Experiment 1 (modal colour choice for the nearest colour in the [43] database).

First, we compared non-synaesthetes in our new dataset to non-synaesthetes in our old dataset. Did the new instructions change non-synaesthetes' behaviour? Indeed, non-synaesthetes in our new data, who were explicitly instructed that black/white/grey were valid responses, were likelier to choose at least one achromatic colour than non-synaesthetes in our old data (76.1% of new subjects versus 53.8% of old subjects, $\chi^2_1 = 8.95$, $p < 0.005$, $RR = 1.42$). Furthermore, the proportion of non-synaesthetes in our new data who chose at least one achromatic colour was not significantly different from the proportion of synaesthetes who chose at least one achromatic colour (76.1% versus 83.3%, $\chi^2_1 = 1.55$, $p = 0.21$, $RR = 1.10$). Thus, there is evidence that at least some non-synaesthetes in our first group may have misunderstood the task instructions.

Next, we replicated the analysis and visualization for figure 1*h* (χ^2-residuals for the associations of synaesthetes versus non-synaesthetes), but with our new non-synaesthetes given explicit instructions that achromatic responses are valid. Figure 4 depicts the standardized χ^2-residual [44] for each colour (positive values mean that the association is likelier in synaesthetes, while associations with negative values are likelier in non-synaesthetes). These residuals are approximately normally distributed, and can be used as a moderately conservative post-hoc test [45] to determine which colour(s) significantly contributed to the overall χ^2-value. The dashed lines depict cut-off points for the $p < 0.05$

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

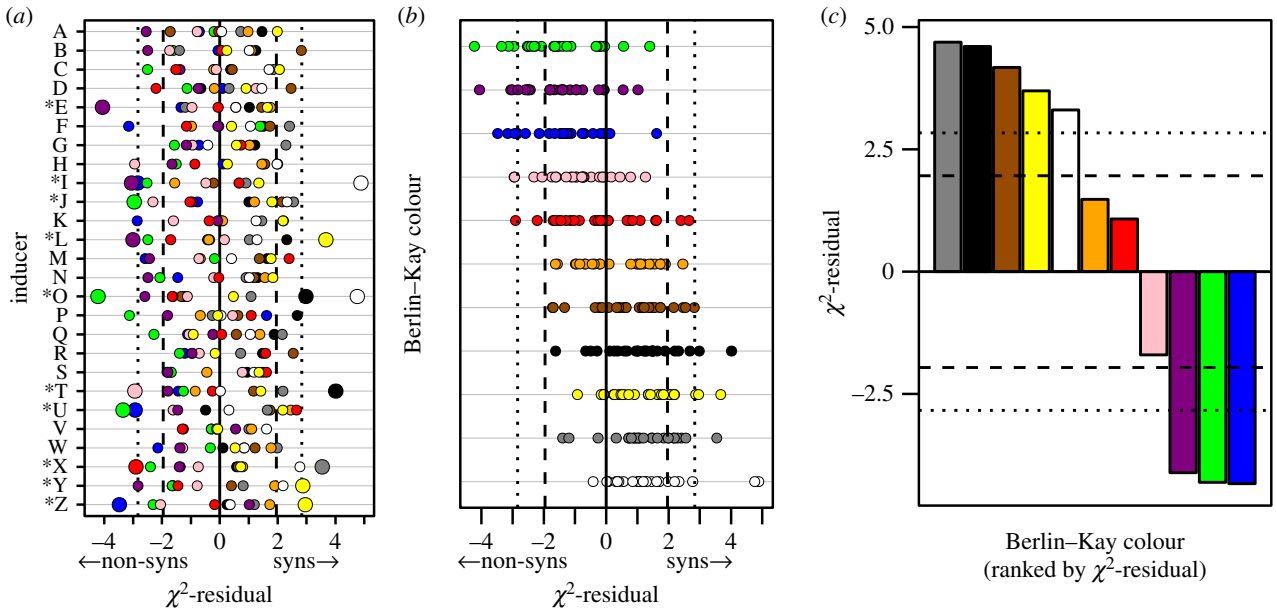

Figure 3. (*a*) χ^2-residuals for each colour for each letter, for the null hypothesis that synaesthetes and synaesthetes' colour associations are the same. The four dashed lines depict cut-off points for the $p < 0.05$ threshold, either uncorrected (large dash) or corrected within letter (small dash). Asterisks indicate that the omnibus per-letter χ^2-test was significant ($p < 0.05$, Bonferroni-corrected). Large circles indicate, for each significant omnibus result, which χ^2-residuals were significant ($p < 0.05$, Bonferroni-corrected). (*b*) The same points as in (*a*), but plotted as a function of colour category instead of inducer. (*c*) The standardized residuals of a χ^2-test of independence for the distribution of Berlin–Kay colour associations for synaesthetes versus non-synaesthetes, after removing letters for which there was a per-letter significant difference between synaesthetes and non-synaesthetes (asterisks in *a*). The large dashed lines are uncorrected $p < 0.05$ thresholds for significance; the small dashed lines are Bonferroni-corrected $p < 0.05$ thresholds.

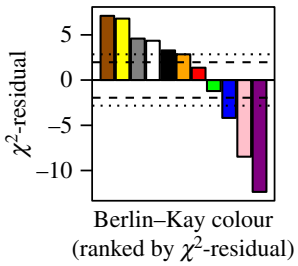

Figure 4. The standardized residuals of a χ^2-test of independence for the distribution of Berlin–Kay colour associations for synaesthetes versus non-synaesthetes *who were instructed that black, white, and grey were valid responses*. The large dashed lines are uncorrected $p < 0.05$ thresholds for significance; the small dashed lines are Bonferroni-corrected $p < 0.05$ thresholds.

threshold, either uncorrected (large dash) or Bonferroni-corrected for 11 comparisons (small dash).

Comparing the residuals in figure 4 to the residuals in figure 1*h*, it is clear that in addition to replicating our result that warm colours are more common in synaesthetes and cool colours are more common in non-synaesthetes, we also replicate our result with achromatic colours: even non-synaesthetes who are explicitly instructed that black/white/grey are valid responses still choose achromatic colours significantly less frequently than synaesthetes (all $p < 0.05$, Bonferroni-corrected).

One additional potential confound is that achromatic associations might yield higher test–retest accuracy: subjects who report many achromatic associations may look particularly consistent only because it is trivially easy to choose pure black or white using a colour picker; in other words, the Eagleman test may produce more false positives when more achromatic colours are picked. To control for this possibility, we recalculated the consistency scores for all synaesthetes with eight or more achromatic associations (no non-synaesthete in our dataset chose more than seven achromatic colours), using only their chromatic associations. In this analysis, 100% (25/25) of the subjects would still qualify as synaesthetes if their achromatic associations were removed (mean consistency: 71.3; max consistency: 108; synaesthesia criterion: consistency < 135).

(ii) Conclusion

After controlling for both confounds, synaesthetes still experience significantly more achromatic associations than non-synaesthetes. Changing task instructions *did* influence non-synaesthetes' responses: more non-synaesthetes chose achromatic colours when explicitly instructed that these were valid responses (either because it eliminated subjects' misunderstanding or because it primed subject responses). Nevertheless, synaesthetes still reported more achromatic associations than non-synaesthetes, when only the non-synaesthetes receive task instructions inviting achromatic colour choices. In other words, the result that synaesthetes experience more achromatic concurrents cannot be explained by non-synaesthetes misinterpreting task instructions.

(g) Experiment 3C: did the testing methods (colour picker) influence the distribution of colour associations?

A subtler potential confound of experimental design is the nature of the Eagleman Battery's colour picker. In this battery, subjects choose hue with a colour slider scaled in the HSV colour space. HSV space is perceptually non-uniform, and the spatial array of the colour picker does not translate equally into Berlin–Kay colour categories. Consistent with Simner *et al.* [12], our non-synaesthetes clearly make some non-random colour associations: for example, associating

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

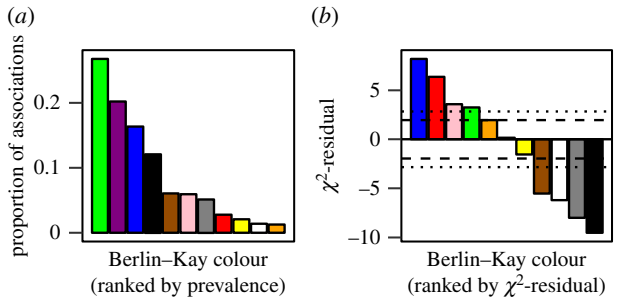

Figure 5. (*a*) The 'random palette': the distribution of colours obtained when sampling uniformly using the Eagleman Battery Colour Picker. (*b*) The residuals of a χ^2-goodness-of-fit test of the non-synaesthetes' palette to a distribution that accounts for non-synaesthetes propensity to choose some associations randomly. The large dashed lines are uncorrected $p < 0.05$ thresholds for significance; the small dashed lines are Bonferroni-corrected $p < 0.05$ thresholds.

'A' with red (51% of non-synaesthetes) and 'G' with green (42% of non-synaesthetes). However, it is plausible that non-synaesthetes select colours randomly on a subset of trials. Critically, cool colours (specifically: green, blue and purple) occupy a large amount of HSV space, suggesting that the warm/cool difference in the synaesthetic and non-synaesthetic 'palettes' might be explained by non-synaesthetes sometimes choosing colours randomly.

(i) Methods and results

To control for this confound, we created a computer simulation of picking random points in the Eagleman Battery, and simulated the trials of 200 'subjects'. This yielded a 15 600 data point sample (200 'subjects' × 26 letters × 3 repeats) of the 'random palette', the distribution of colours expected when a subject selects colours randomly on the Eagleman Colour Picker (figure 5*a*). While the random palette is not identical to the non-synaesthetic palette (compare figure 5*a* to figure 1*g*), it is notable that the most common colours in the random palette (green, blue and purple, blue) are also over-represented in the non-synaesthetic palette.

(ii) Results

To quantify this observation, we constructed a model in which the non-synaesthetic palette is a proportional combination of the synaesthetic palette and the random palette (e.g. a non-synaesthete who chooses randomly on 10% of trials will have the distribution of associations 0.9(synaesthetic palette) + 0.1(random palette)). We used grid search (step size: 1%) to determine for each subject the number of random choices that best explained the subject's palette. On average, the non-synaesthetic palette was best explained by assuming that non-synaesthetes choose randomly on 37.6% of trials. Per subject, the model estimate varied widely (from 0 to 100%) but critically, the model estimate was strongly correlated with test–retest consistency score ($t_{91} = 5.447$, $p < 0.0001$, $r = 0.495$). This correlation thus supports our approach of using the model as a way to measure the degree in which a non-synaesthete's palette is random: subjects whose palettes more-closely resembled the random palette performed worse on test–retest consistency, as would be expected if they were choosing more randomly.

Next, we can compare our 'random colour' model's predictions to the observed palette of non-synaesthetes using a χ^2-goodness-of-fit test, and examine the residuals using the same methods as Experiment 1. Significant residuals here indicate differences between the synaesthetic and non-synaesthetic palette that *cannot be attributed to non-synaesthetes choosing some associations randomly*. Figure 5*b* depicts the residuals of this test. The purple residual is no longer significant (unlike in figure 1*h*), suggesting that the preponderance of purple associations in non-synaesthetes can be attributed to non-synaesthetes choosing randomly. However, the other cool colours (green, blue, pink) are still significantly more common in non-synaesthetes than synaesthetes, even *after* accounting for non-synaesthetes tendency to choose randomly on some subset of trials.

(iii) Conclusion

Random choices by non-synaesthetes can explain part, *but not all*, of the 'warm/cool' difference between the synaesthetic and non-synaesthetic palette. This has important implications in the design of control conditions for experiments that compare synaesthetes and non-synaesthetes; using the colour picker in the Eagleman test battery biases particular colour categories, and results would need to be compared with simulations of random colour picking, as we have done here. Our finding is consistent with previous results that when non-synaesthetes instead supply written colour labels, there is a relationship between non-synaesthetes' colour choices and ease-of-generation (the distribution that would be expected if non-synaesthetes were randomly *naming* colours, [12]). In other words, test design in general exerts a measurable influence on non-synaesthetic colour associations. Nevertheless, random choice is not the sole reason for obtaining the non-synaesthetes' 'cool' palette: non-synaesthetes still experience more 'cool' colours than synaesthetes, even after controlling for their increased propensity to choose colours randomly.

3. Discussion

We have shown, for the first time, that the set of synaesthetic colours in colour space (which we termed the 'synaesthetic colour palette') is sufficient to reliably predict whether an individual is a synaesthete or not. Furthermore, we have shown three particular characteristics of this synaesthetic colour palette. First, we found that the over-representation of unique hues (pure shades of red, green, blue and yellow) was more pronounced in synaesthetes than in non-synaesthetes. Second, compared to non-synaesthetes, synaesthetes' colour palettes contained more 'warm' (Berlin–Kay colour categories yellow, brown and orange) colours and fewer 'cool' colours (Berlin–Kay colour categories green, blue, purple and pink). However, red colour choices did not differ between synaesthetes and non-synaesthetes. Third, compared to non-synaesthetes, synaesthetes' colour palettes contained more achromatic (black, grey and white) colours.

An important limitation in the interpretation of the current results lies in the commonly used strategy of using consistency as the gold standard in screening for synaesthesia. The current study mainly shows a relationship between synaesthesia as screened based on consistency, and the set of colour concurrents experienced by these presumptive synaesthetes. While consistency is an important characteristic of synaesthesia, it is not a sufficient condition for having synaesthesia. The conscious, automatic, percept-like, involuntary and effortless nature of the experiences is another critical aspect of synaesthesia that

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

unfortunately we had no opportunity to include in our current analyses. We can therefore not relate these characteristics to the current findings, and this is an important topic for follow-up research. Indeed, a related limitation is that approximately 10% of self-reported synaesthetes do not qualify as synaesthetes by the standard threshold used to screen synaesthesia in online consistency studies [41]. One important question is therefore whether our study's conclusions also apply to synaesthetes who do not meet this consistency threshold: do these synaesthetes also have a warmer and more achromatic palette? This points at a broader important current issue in synaesthesia research: how the different measurements of synaesthesia (e.g. the Stroop effect, localization, automaticity/attention and consistency scores, [48]) do, or do not, align. Future research should compare each of these diagnostics (including the 'palette' score from Experiment 2) to determine whether their predictions overlap, and for example, whether future experiments should verify synaesthesia using some combination of diagnostics rather than consistency alone. In such a line of research, it would be useful to contrast individual differences in the *nature* of synaesthetic experiences as well ('in the mind only' versus 'in the outside world') as previous findings have indicated that these differential experiences reflect differences in the underlying synaesthetic mechanisms [49–51]. Finally, there are more differences between synaesthetes and non-synaesthetes than these defining characteristics, such as enhanced imagery, increased creativity, higher IQ, improved memory performance, particular personality profile, and so on [52–56], each potentially pointing at explanatory (mechanistic) cognitive and neuroscientific differences between synaesthetes and non-synaesthetes.

While our results show clear (colour) characteristics on which synaesthetes are different from non-synaesthetes, we have not determined what drives these observed differences. We did formulate a few 'trivial' causal hypotheses (which failed to explain results) in Experiment 3. In follow-up research, more interesting causal explanations could be tested. This would increase our understanding of the mechanisms underlying synaesthesia; logically, the differences between synaesthetic and non-synaesthetic colour patterns are indicative of influences on colour concurrents that are unique to synaesthetes. In a contemporaneous publication [25], we showed how a particular grapheme-colour association present in adult synaesthetes, but not present in non-synaesthete colour associations, could be traced to a particular environmental effect in early childhood (a preference for the colour 'pink' in young girls). Previous literature has supported relative over-representation of influences related to learning processes taking place during the development of grapheme-colour synaesthesia in early childhood [13,57,58]. However, it is not clear yet which mechanisms underlie the development of synaesthesia, nor what are the similarities and differences with 'normal' (non-synaesthete) development.

What explains the specific colours in the synaesthetic colour palette is an interesting topic for future research. Colour preferences change through development in a direction consistent with differences in the synaesthetic palette: in a study comparing colour preferences at age 7, 11 and adulthood, Terwogt & Hoeksma [59] found a monotonic increase with age in preference for blue, and a monotonic decrease with age in preference for yellow. Alternatively, the differences in palettes could be attributed to the nature of synaesthetic associations as 'real' or 'concrete' [2] rather than abstract: objects (compared to backgrounds) in natural scenes are likelier to have warm colours than cool colours [60], so perhaps synaesthetes view letters as 'objects' and match their colour palette to scene statistics of the natural world. Finally, we notice that the synaesthetic palette is approximately evenly divided between warm and cool colours, which, respectively, have a positive versus negative value of the L-M cone contrast [61]. This could be consistent with suggestions that synaesthetic colour processing is influenced by early colour-opponent channels [62].

(a) In sum

In this study, we characterized the synaesthetic palette: a consistent difference in the set of colours experienced by synaesthetes versus non-synaesthetes. Future research may shed light into the mechanisms which cause this difference. For now, we demonstrate for the first time that such a difference between synaesthetes and non-synaesthetes exists, and that this difference can be used to 'diagnose' synaesthesia based only on the set of colours a subject reports.

Data accessibility. The supporting datasets and scripts are available in electronic supplementary material.

Authors' contributions. R.R. conceived of the project idea; R.R. and N.B.R. designed the experiments and wrote the manuscript and the revised manuscript; N.B.R. did data analyses and visualizations. All authors gave final approval for publication and agree to be held accountable for the work performed therein.

Competing interests. We declare we have no competing interests.

Funding. We received no funding for this study.

Acknowledgements. We thank V.S. Ramachandran and David Brang for facilitating data collection.

References

1. Jewanski J. 2013 Synesthesia in the nineteenth century: scientific origins. In *Oxford library of psychology. The Oxford handbook of synaesthesia* (eds J Simner, EM Hubbard), pp. 369–398. New York, NY: Oxford University Press.
2. Palmeri TJ, Blake R, Marois R, Flanery MA, Whetsell W. 2002 The perceptual reality of synaesthetic colors. *Proc. Natl Acad. Sci. USA* **99**, 4127–4131. (doi:10.1073/pnas.022049399)
3. Lovelace CT. 2013 Synesthesia in the twenty-first century. In *Oxford library of psychology. The Oxford handbook of synaesthesia* (eds J Simner, EM Hubbard), pp. 369–398. New York, NY: Oxford University Press.
4. Colizoli O, Murre JM, Rouw R. 2014 Defining (trained) grapheme-color synaesthesia. *Front. Hum. Neurosci.* **8**, 368. (doi:10.3389/fnhum.2014.00368)
5. Grossenbacher PG, Lovelace CT. 2001 Mechanisms of synaesthesia: cognitive and physiological constraints. *Trends Cogn. Sci.* **5**, 36–41. (doi:10.1016/S1364-6613(00)01571-0)
6. Newell FN, Mitchell KJ. 2016 Multisensory integration and cross-modal learning in synaesthesia: a unifying model. *Neuropsychologia* **88**, 140–150. (doi:10.1016/j.neuropsychologia.2015.07.026)
7. Ramachandran VS, Hubbard EM. 2001 Synaesthesia—a window into perception, thought and language. *J. Conscious. Stud.* **8**, 3–34.
8. Simner J. 2012 Defining synaesthesia. *Br. J. Psychol.* **103**, 1–15. (doi:10.1348/000712610X528305)
9. Shriki O, Sadeh Y, Ward J. 2016 The emergence of synaesthesia in a Neuronal Network Model via

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022

changes in perceptual sensitivity and plasticity. *PLoS Comput. Biol.* **12**, e1004959. (doi:10.1371/journal.pcbi.1004959)

10. Asher JE, Aitken MR, Farooqi N, Kurmani S, Baron-Cohen S. 2006 Diagnosing and phenotyping visual synaesthesia: a preliminary evaluation of the revised test of genuineness (TOG-R). *Cortex* **42**, 137–146. (doi:10.1016/S0010-9452(08)70337-X)
11. 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. (doi:10.1016/j.jneumeth.2006.07.012)
12. Simner J, Ward J, Lanz M, Jansari A, Noonan K, Glover L, Oakley DA. 2005 Non-random associations of graphemes to colours in synaesthetic and non-synaesthetic populations. *Cogn. Neuropsychol.* **22**, 1069–1085. (doi:10.1080/02643290500200122)
13. Rich AN, Bradshaw JL, Mattingley JB. 2005 A systematic, large-scale study of synaesthesia: implications for the role of early experience in lexical-colour associations. *Cognition* **98**, 53–84. (doi:10.1016/j.cognition.2004.11.003)
14. Brang D, Rouw R, Ramachandran VS, Coulson S. 2011 Similarly shaped letters evoke similar colors in grapheme–color synaesthesia. *Neuropsychologia* **49**, 1355–1358. (doi:10.1016/j.neuropsychologia.2011.01.002)
15. Watson MR, Akins KA, Enns JT. 2012 Second-order mappings in grapheme–color synaesthesia. *Psychon. Bull. Rev.* **19**, 211–217. (doi:10.3758/s13423-011-0208-4)
16. Kang MJ, Kim Y, Shin JY, Kim CY. 2017 Graphemes sharing phonetic features tend to induce similar synaesthetic colors. *Front. Psychol.* **8**, 337. (doi:10.3389/fphys.2017.00337)
17. Asano M, Yokosawa K. 2011 Synesthetic colors are elicited by sound quality in Japanese synaesthetes. *Conscious. Cogn.* **20**, 1816–1823. (doi:10.1016/j.concog.2011.05.012)
18. Beeli G, Esslen M, Jäncke L. 2007 Frequency correlates in grapheme-color synaesthesia. *Psychol. Sci.* **18**, 788–792. (doi:10.1111/j.1467-9280.2007.01980.x)
19. Asano M, Yokosawa K. 2012 Synesthetic colors for Japanese late acquired graphemes. *Conscious. Cogn.* **21**, 983–993. (doi:10.1016/j.concog.2012.02.005)
20. Spector F, Maurer D. 2011 The colors of the alphabet: naturally-biased associations between shape and color. *J. Exp. Psychol. Hum. Percept. Perform.* **37**, 484. (doi:10.1037/a0021437)
21. Witthoft N, Winawer J. 2006 Synesthetic colors determined by having colored refrigerator magnets in childhood. *Cortex* **42**, 175–183. (doi:10.1016/S0010-9452(08)70342-3)
22. Witthoft N, Winawer J. 2013 Learning, memory, and synaesthesia. *Psychol. Sci.* **24**, 258–265. (doi:10.1177/0956797612452573)
23. Rouw R, Case L, Gosavi R, Ramachandran VS. 2014 Color associations for days and letters across different languages. *Front. Psychol.* **5**, 369. (doi:10.3389/fpsyg.2014.00369)
24. Mankin JL, Simner J. 2017 A is for apple: the role of letter–word associations in the development of grapheme–colour synaesthesia. *Multisens. Res.* **30**, 409–446. (doi:10.1163/22134808-00002554)
25. Root NB, Dobkins K, Ramachandran VS, Rouw R. 2019 Echoes from the past: synaesthetic colour associations reflect childhood gender stereotypes. *Phil. Trans. R. Soc. B* **374**, 20180572. (doi:10.1098/rstb.2018.0572)
26. Van Leeuwen TM, Dingemanse M, Todil B, Agameya A, Majid A. 2016 Nonrandom associations of graphemes with colors in Arabic. *Multisensory Res.* **29**, 223–252. (doi:10.1163/22134808-00002511)
27. Jakobson R. 1962 *Selected writings I. Phonological studies*. The Hague, The Netherlands: Mouton & Co.
28. Marks LE. 1975 On colored-hearing synaesthesia: cross-modal translations of sensory dimensions. *Psychol. Bull.* **82**, 303–331. (doi:10.1037/0033-2909.82.3.303)
29. Ward J, Huckstep B, Tsakanikos E. 2006 Sound-colour synaesthesia: to what extent does it use cross-modal mechanisms common to us all? *Cortex* **42**, 264–280. (doi:10.1016/S0010-9452(08)70352-6)
30. Wrembel M. 2009 On hearing colours—cross-modal associations in vowel perception in a non-synaesthetic population. *Poznań Stud. Contemp. Ling.* **45**, 581–598. (doi:10.2478/v10010-009-0028-0)
31. Guillamon PM. 2014 Vowel–colour symbolism in English and Arabic: a comparative study. *Miscelánea* **47**, 31–52.
32. Moos A, Smith R, Miller SR, Simmons DR. 2014 Cross-modal associations in synaesthesia: vowel colours in the ear of the beholder. *i-Perception* **5**, 132–142. (doi:10.1068/i0626)
33. Kim H-W, Nam H, Kim C-Y. 2018 [i] is lighter and more greenish than [o]: intrinsic association between vowel sounds and colors. *Multis. Res.* **31**, 419–437. (doi:10.1163/22134808-00002581)
34. Mok PP, Li G, Li JJ, Ng HT, Cheung H. 2019 Cross-modal association between vowels and colours: a cross-linguistic perspective. *J. Acoust. Soc. Am.* **145**, 2265–2276. (doi:10.1121/1.5096632)
35. Cuskley C, Dingemanse M, Kirby S, van Leeuwen TM. 2019 Cross-modal associations and synaesthesia: categorical perception and structure in vowel-colour mappings in a large online sample. *Behav. Res. Methods* **51**, 1651–1675. (doi:10.3758/s13428-019-01203-7)
36. Kadosh RC, Henik A. 2007 Can synaesthesia research inform cognitive science? *Trends Cogn. Sci.* **11**, 177–184. (doi:10.1016/j.tics.2007.01.003)
37. Kusnir F, Thut G. 2012 Formation of automatic letter–colour associations in non-synaesthetes through likelihood manipulation of letter–colour pairings. *Neuropsychologia* **50**, 3641–3652. (doi:10.1016/j.neuropsychologia.2012.09.032)
38. Deroy O, Spence C. 2013 Why we are not all synaesthetes (not even weakly so). *Psychon. Bull. Rev.* **20**, 643–664. (doi:10.3758/s13423-013-0387-2)
39. Hamada D, Yamamoto H, Saiki J. 2017 Database of synesthetic color associations for Japanese kanji. *Behav. Res. Methods* **49**, 242–257. (doi:10.3758/s13428-015-0691-z)
40. Root NB, Rouw R, Asano M, Kim CY, Melero H, Yokosawa K, Ramachandran VS. 2018 Why is the synaesthete's 'A' red? Using a five-language dataset to disentangle the effects of shape, sound, semantics, and ordinality on inducer–concurrent relationships in grapheme-color synaesthesia. *Cortex* **99**, 375–389. (doi:10.1016/j.cortex.2017.12.003)
41. Rothen N, Seth AK, Witzel C, Ward J. 2013 Diagnosing synaesthesia with online colour pickers: maximising sensitivity and specificity. *J. Neurosci. Methods* **215**, 156–160. (doi:10.1016/j.jneumeth.2013.02.009)
42. Berlin B, Kay P. 1969 *Basic color terms: their universality and evolution*. Berkeley, CA: University of California Press.
43. Jraissati Y, Douven I. 2018 Delving deeper into color space. *i-Perception* **9**, 1–27. (doi:10.1177/2041669518792062)
44. Agresti A, Franklin CA. 2007 *Statistics: the art and science of learning from data*. Upper Saddle River, NJ: Pearson Prentice Hall.
45. MacDonald PL, Gardner RC. 2000 Type I error rate comparisons of post hoc procedures for I j chi-square tables. *Educ. Psychol. Meas.* **60**, 735–754. (doi:10.1177/00131640021970871)
46. Dimitriadou E, Hornik K, Leisch F, Meyer D, Weingessel A. 2008 Misc functions of the Department of Statistics (e1071), TU Wien. *R package* **1**, 5–24.
47. Powers DMW. 2011 Evaluation: From precision, recall and F-Score to ROC, informedness, markedness & correlation. *J. Mach. Learn. Technol.* **2**, 37–63.
48. Rothen N, Tsakanikos E, Meier B, Ward J. 2013 Coloured Letters and Numbers (CLaN): a reliable factor-analysis based synaesthesia questionnaire. *Conscious. Cogn.* **22**, 1047–1060. (doi:10.1016/j.concog.2013.07.005)
49. Dixon MJ, Smilek D. 2005 The importance of individual differences in grapheme-color synaesthesia. *Neuron* **45**, 821–823. (doi:10.1016/j.neuron.2005.03.007)
50. Ward J, Li R, Salih S, Sagiv N. 2007 Varieties of grapheme-colour synaesthesia: a new theory of phenomenological and behavioural differences. *Conscious. Cogn.* **16**, 913–931. (doi:10.1016/j.concog.2006.09.012)
51. Rouw R, Scholte HS. 2010 Neural basis of individual differences in synaesthetic experiences. *J. Neurosci.* **30**, 6205–6213. (doi:10.1523/JNEUROSCI.3444-09.2010)
52. 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? *Pers. Indiv. Diff.* **54**, 828–831. (doi:10.1016/j.paid.2012.12.018)
53. Mulvenna CM. 2013 Synesthesia and creativity. In *Oxford library of psychology. The Oxford handbook of synaesthesia* (eds J Simner, EM Hubbard), pp. 607–630. New York, NY: Oxford University Press.

54. Rothen N, Meier B, Ward J. 2012 Enhanced memory ability: insights from synaesthesia. *Neurosci. Biobehav. Rev.* **36**, 1952–1963. (doi:10.1016/j.neubiorev.2012.05.004)
55. Rouw R, Scholte HS. 2016 Personality and cognitive profiles of a general synaesthetic trait. *Neuropsychologia* **88**, 35–48. (doi:10.1016/j.neuropsychologia.2016.01.006)
56. Spiller MJ, Jonas CN, Simner J, Jansari A. 2015 Beyond visual imagery: how modality-specific is enhanced mental imagery in synaesthesia? *Conscious. Cogn.* **31**, 73–85. (doi:10.1016/j.concog.2014.10.010)
57. Simner J, Harrold J, Creed H, Monro L, Foulkes L. 2008 Early detection of markers for synaesthesia in childhood populations. *Brain* **132**, 57–64. (doi:10.1093/brain/awn292)
58. Witthoft N, Winawer J, Eagleman DM. 2015 Prevalence of learned grapheme-color pairings in a large online sample of synaesthetes. *PLoS ONE* **10**, e0118996. (doi:10.1371/journal.pone.0118996)
59. Terwogt MM, Hoeksma JB. 1995 Colors and emotions: preferences and combinations. *J. Gen. Psychol.* **122**, 5–17. (doi:10.1080/00221309.1995.9921217)
60. Gibson E, Futrell R, Jara-Ettinger J, Mahowald K, Bergen L, Ratnasingam S, Gibson M, Piantadosi ST, Conway BR. 2017 Color naming across languages reflects color use. *Proc. Natl Acad. Sci. USA* **114**, 10 785–10 790. (doi:10.1073/pnas.1619666114)
61. Xiao Y, Kavanau C, Bertin L, Kaplan E. 2011 The biological basis of a universal constraint on color naming: cone contrasts and the two-way categorization of colors. *PLoS ONE* **6**, e24994. (doi:10.1371/journal.pone.0024994)
62. Nikolić D, Lichti P, Singer W. 2007 Color opponency in synaesthetic experiences. *Psychol. Sci.* **18**, 481–486. (doi:10.1111/j.1467-9280.2007.01925.x)

Downloaded from https://royalsocietypublishing.org/ on 03 January 2022