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NON-RANDOM ASSOCIATIONS OF GRAPHEMES TO COLOURS IN SYNAESTHETIC AND NON-SYNAESTHETIC POPULATIONS

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This study shows that biases exist in the associations of letters with colours across individuals both with and without grapheme–colour synaesthesia. A group of grapheme–colour synaesthetes were significantly more consistent over time in their choice of colours than a group of controls. Despite this difference, there were remarkable inter-subject agreements, both within and across participant groups (e.g., *a* tends to be red, *b* tends to be blue, *c* tends to be yellow). This suggests that grapheme–colour synaesthesia, whilst only exhibited by certain individuals, stems in part from mechanisms that are common to us all. In addition to shared processes, each population has its own distinct profile. Synaesthetes tend to associate higher frequency graphemes with higher frequency colour terms. For control participants, choices are influenced by order of elicitation, and by exemplar typicality from the semantic class of colours.

Synaesthesia is a familial condition (e.g., Ward & Simner, in press) in which perceptual and cognitive activities trigger incongruous sensory percepts. For example, colours may be experienced in response to smells (Cytowic, 1993) and tastes in response to words (Ward & Simner, 2003). Brain imaging techniques have illustrated the neurological basis of the condition and its similarity to

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veridical perception. Nunn, Gregory, Brammer, Williams, Parslow, Morgan et al. (2002) showed that synaesthetic colour induced by spoken words produces fMRI activation in areas normally associated with the colour perception of external stimuli (left V4). This activation was triggered by words but not tones, and provides evidence that synaesthetic experiences are genuine and perceptual. In this paper, we investigate the roots of synaesthetic associations, and question whether synaesthetic phenomena reflect an exaggeration of mechanisms for cross-modal association that are common to us all. We focus on one of the most prevalent developmental variants, namely that between graphemes and colours (e.g., Rich & Mattingley, 2002; Simner, Glover, & Mowat, in press; Ward, Simner, & Auyeung, 2005). One account of grapheme–colour synaesthesia is based on the observation that a region of the brain responsible for colour perception (V4) lies close to the region involved in grapheme recognition. It has been suggested that this proximity could lead to "cross-activation" of the adjacent areas due to the growth of neural connections, or because of failure to remove such connections at an early age (e.g., Maurer, 1997; Ramachandran & Hubbard, 2001). We assess whether underlying principles exist to determine why particular graphemes become associated with particular colours, and whether the same principles operate across both synaesthetic and normal populations.

On the surface, the claim that synaesthesia might reflect an exaggeration of normal cross-modal perception appears to fit better with some forms of the condition than with others. For example, it is well established that specialised mechanisms exist in the brain for uniting information from the sensory modalities of vision and sound (e.g., Calvert, 2001). It is tempting to conclude that certain forms of synaesthesia might tap these cross-modal mechanisms and there is some preliminary evidence to support this. For example, music–colour synaesthetes tend to experience dark colours for low pitched tones and light colours for high pitched tones (e.g., Marks, 1975; Riggs & Karwoski, 1934; Ward, Huckstep, & Tsakanikos, in press; Zigler, 1930) and the same trend is found in the normal population (e.g., Hubbard, 1996; Marks, 1974; Simpson, Quinn, & Ausubel, 1956). Synaesthetes may differ from non-synaesthetes in terms of the consistency of their responses, their automaticity, and their reported phenomenology, but the mechanisms that guide the choice of cross-modal associations appear to be common to both synaesthetes and non-synaesthetes alike. To what extent, however, might this be true of all forms of synaesthesia? On the surface at least, the grapheme–colour variant seems a good case in point that synaesthesia may not always reflect an exaggeration of normal/innate processes. First, models of normal cognition do not postulate links between graphemes and colours, in the same way as they do for sound and vision. Second, it is not clear exactly how innate mechanisms might govern the association of colours to graphemes, since these latter are abstract symbols that are culturally acquired. Finally, it has been claimed that the mappings between graphemes and colours are idiosyncratic even within the synaesthetic population (e.g., Galton, 1883/1997; Jordan, 1917) which suggests, on the surface at least, that there are no common underlying principles extending across individuals.

The aim of the current study is to show that regularities can indeed be found in the reports of grapheme–colour synaesthetes, and those of non-synaesthetic participants asked to generate analogous associations. We will show that while not *all* participants agree upon their colours, structured biases nonetheless exist, in that some grapheme–colour combinations are selected more often than one would expect by chance. Indeed, two previous studies that have adopted a similar approach to us have suggested certain significant regularities, in the synaesthetic population at least. Baron-Cohen, Harrison, Goldstein, and Wyke (1993) performed a meta-analysis of grapheme–colour associations by combining their own cases of synaesthesia with a set from the historical literature. They show, for example, that the letter *o* is associated with the colour white in 73% of synaesthetes, and that this was significantly different from chance.

Day (2001, 2005) too, found trends in the grapheme–colour mappings of a large sample of self-reported synaesthetes, and in a selection of cases from the historical literature. The letter *a* was typically red, *b* was often blue, *c* was often yellow, *i* was often either black or white and so on. Although these results are intriguing, there is reason for caution in their interpretation. First, most contemporary studies of synaesthesia are required to provide objective measures to show that their synaesthete participants represent genuine cases. The most commonly used method for grapheme–colour synaesthesia is consistency over time (e.g., Baron-Cohen et al., 1993) or Stroop-like interference from synaesthetic colours (e.g., Mattingley, Rich, Yelland, & Bradshaw, 2001). The studies by Day (2001, 2005) did not provide this assessment, although we aim to do so with our own sample. Additionally, we extend Day's line of research by considering whether non-synaesthetes, despite being more inconsistent over time, nevertheless have a tendency to select the same distribution of colours as synaesthetes (e.g., *a* tending to be red, *b* tending to be blue).

Our research also examines the origins of any grapheme–colour regularities, and considers factors such as letter ordering, letter frequency, colour name frequency, colour typicality (from the semantic class), and the native language of the speaker. Our synaesthetes are compared to four control groups, according to population and procedure variations. We compare two types of instruction (forced- vs. free-choice) to test whether biases exist even when participants are not obliged to produce any letter–colour associations at all. Additionally, we examine the influence of ordering in the materials list, and, finally, we elicit judgements from non-synaesthete native German speakers, in order to compare their associations with comparable English data. If biases are derived from factors shared across languages (e.g., the visual forms of letters) then German and English speakers should generate similar colour associations. However, if biases stem from factors that differ, such as letter names (cf. *y* = *wye* in English, but *yot* in German), colour-terms (e.g., *purple* vs. *lila*) or other influences, then cross-linguistic differences may be found.

EXPERIMENTAL INVESTIGATION

Participants

Synaesthete participants

Seventy native-English speaking synaesthetes (15 male, 55 female; mean age = 43.8) were recruited from the database of the British Synaesthesia Research Consortium. Each reported colours associated with graphemes, although we additionally sought objective measures to establish the genuineness of these reports (see Test of Genuineness, below).

Control participants

Three hundred and seventeen English speaking control participants (81 male, 236 female; mean age = 21.6) were recruited from the university communities of Edinburgh and London. A further 58 German speaking controls (21 male, 37 female; mean age = 38.0) were recruited from the local populations of Kappeln and Nuremberg. Control participants had been screened to ensure that none experienced synaesthetic perception. For screening, participants were given a booklet that described the features of synaesthesia and which prompted participants to indicate any form of synaesthesia they thought they may have. Any participant providing any type of affirmative response was excluded from the control group.

Procedure

Our analyses are based on the grapheme–colour associations generated by our participants, whose responses were elicited with the following methodologies. Synaesthete participants were given a written questionnaire that asked them to state any colour associations for the 26 letters of the alphabet, presented in order. They were also given a second list, with the same instructions for the numerals *0–9*.

Our English-speaking controls were randomly allocated to one of three groups. Sixty-two controls (21 male; 41 female) were presented with the same alphabetical list as our synaesthetes, and instructed to write down the first colour that came to mind for all 26 letters (Forced-choice controls). A second group of 195 controls (39 male; 156 female) were given the same list, and asked to note a colour if one came easily to mind, but were not forced to generate a colour for any letter if none was forthcoming (Free-choice controls). The third group of 30 participants (14 male; 16 female) were given forced-choice instructions, but with letters arranged in one of five randomised orders (Randomised controls). Our final control group comprised our 58 German controls, who were given free-choice instructions, and a non-randomised, alphabetical list to which they wrote their colour associations. The group was tested in German, with German instructions, and by a native German speaker in Germany. Controls in all four groups were required to chose the first colour that came to mind for each letter, and were told that they could repeat colours if they wished. In all cases, participants were allowed to give as little or as much detail about their colour choices as they wished. Participants were instructed without the use of examples, in order to avoid biasing any particular grapheme–colour choice.

Finally, 35 members of the Forced-choice control group (17 male; 18 female) additionally served as controls for the test of genuineness (see below). These participants were given the list of numerals *0–9*, in order, and were required to write down the first colour that came to mind for each number. Like our synaesthetes, they did this in addition to providing associations for the alphabet list. These 35 controls and all 70 synaesthetes were given a surprise re-test after a pre-determined time interval. For synaesthetes this was 2–6 months, and for controls this was 1–3 weeks. In this way, we "stacked the deck" against our synaesthete participants in order to test them more conservatively. For re-testing, the order of letters and numbers was randomised, and presented to both groups. Synaesthetes were required to re-state their grapheme–colour correspondences, and controls were asked to remember those they had generated in the first round of testing, or to guess if they could no longer remember. Responses were coded as consistent if they used a single colour name twice (*red, blue, green*, etc.) or if two independent coders agreed that the terms were equivalent (e.g., Time 1 = *beige*; Time 2 = *light brown*). Any case of uncertainty was conservatively classed as non-consistent.

Results and discussion

Test of genuineness

Synaesthetes were more consistent over time than control participants, both for letters (92% vs. 36% respectively) and for numbers (93% vs. 35% respectively) and both group differences were significant (Mann Whitney $Z = -8.375$, $p < .001$; $Z = -8.375$, $p < .001$). Furthermore, all 70 individual synaesthetes significantly out-performed controls (all Zs > 2.2; all ps $> .05$). Such differences have traditionally been used to show that synaesthetes are genuine (e.g., Baron-Cohen, Wyke, & Binnie, 1987) in so far as their performance on this test is superior to control participants.[1]

Analyses of overall colour responses

Depth and range of colour descriptions. An examination of responses from synaesthetes and Forced-choice controls revealed that synaesthetes produced a greater depth of colour descriptions

[1] An anonymous reviewer has asked us to point out that our focus on graphemes gives rise to an item list ($n = 36$) that is smaller than some studies (where the synaesthesia is triggered by words; e.g., $n = 80$ in Ward et al., 2005). We tested consistency for all 26 letters, but restricted ourselves to the numerals *0–9* simply because grapheme–colour synaesthetes often report that numbers *10*-and-above are coloured as a combination of their constituents (e.g., *25* is the colour of *2* and *5*). The crucial fact, however, is that our list is *equally sized for both synaesthetes and controls* and that synaesthetes perform significantly better—even with the longer time interval.

and more colour terms. Each of our synaesthete participants produced an average of 45.0 words in their description of the 26 letters of the alphabet, which was significantly higher (both by subjects and items) than the mean of 26.5 for controls, $t_1(130) = 12.3$, $p < .001$; $t_2(25) = 50.33$, $p < .001$. Synaesthetes also produced significantly more colour variants, generating 495 compared to 58 for controls, $t_1(130) = 11.8$, $p < .001$; $t_2(25) = 29.2$, $p < .001$. The range of synaesthetes' colour responses can be seen by considering the category green as an example, for which its 195 responses comprised 54 different colour descriptions (e.g., pea green, jade green, lime green, lettuce green, blackish green, fir tree green, muddy green, bottle green) compared to only five (green, dark green, lime, emerald and avocado) from the 219 green responses of the control participants. These findings may have one of two interpretations. First, people with synaesthesia may simply possess a more extensive vocabulary of colour terms. In this way, differences between synaesthetes and non-synaesthetes may mirror those found between the sexes (Nowaczyk, 1982, Swaringen, Layman, & Wilson, 1978; Thomas, Curtis, & Bolton, 1978). We tentatively favour a second hypothesis, however, in which the greater range of descriptions provided by synaesthetes might derive from the fact that their grapheme–colour associations are more "actual" or existent than those of our controls (who would simply be naming colour terms—rather than experiencing a visual sensation and attempting to describe it accurately; see also Day, 2005). In this way, the quantitative differences in synaesthetes' descriptions may be an additional indication of the genuineness of their reports.

Ease-of-generation

When people are asked to produce a series of colour terms, Battig and Montague (1969) have shown that certain colours tend to be generated earlier and more often than others (e.g., red > purple). Their norms provide an index of exemplar typicality and ease-of-generation for each colour term, and have been used extensively in psychological research (e.g., Chao & Martin, 1999; Conrad, Brown, & Dashen, 2003; Wiggs, Weisberg, & Martin, 1999). If control participants are producing colours according to those that are brought to mind most easily on demand, we predict that their responses will be sensitive to the ordering of the Battig and Montague norms (shown in the Appendix). In contrast, if synaesthetes are producing colour associations that were in existence before the testing session, we expect them to be less sensitive to such measures.

The colour associations generated by our three ordered English groups (Synaesthetes, Forced-choice controls, Free-choice controls) were classified according to a small set of basic colours. Like Day (2005), we chose the 11 irreducible English colour terms from Berlin & Kay (1969; see also Hardin & Maffi, 1997): black, white, red, yellow, green, blue, brown, orange, purple, pink and grey. In most cases, these colour terms had been used in the synaesthete's description (e.g., *pea green*), but where they had not (e.g., *tangerine*), coding was performed by two independent assessors, who agreed on over 99% of codings. (The only disagreement came with the term *maroon*, which coder 1 classed as brown and coder 2 as red. The final coding was based on the OED dictionary definition, which classifies the colour as a (brownish) variant of red.) A small number of colour terms such as *transparent*, which did not fall easily into any category were classified as *other*. Colours were then ranked according to their frequency within each group. For example, the three most common colours for synaesthetes were brown (ranked 1), yellow (ranked 2) and grey (ranked 3). For controls these were yellow, blue, green (Forced-choice group) and green, blue yellow (Free-choice group). Spearman's Rho comparisons with the Battig and Montague rankings show a qualitatively different pattern of colour choices between synaesthetes and controls. For both Forced-choice and Free-choice controls, there was a significant positive correlation between colour frequency and the Battig and Montague orderings ($\rho = .86$, $p < .01$; $\rho = .92$, $p < .001$, respectively) such that the most frequently produced colours were those ranked highest for typicality/ease-of-generation. In contrast, there was no such correlation for synaesthetes ($\rho = -.02$, $p = ns$) suggesting that these latter were not simply producing grapheme–colour associations "off-the-cuff", in a way that might be reflected by a predominance of easy-to-generate colours (see also Day, 2005, who makes a similar observation). Such a finding again suggests that grapheme–colour associations for synaesthetes may be something durable and constant, rather than spontaneously generated by the demands of our task.

Analyses of grapheme–colour associations

In the analyses that follow, we determined whether any between-subject consistencies exist in grapheme–colour pairings, both for synaesthetes and for controls, and whether any consistencies are shared between groups. We then consider possible mechanisms that might account for the letter–colour correspondences chosen by our participants.

Do synaesthetes and/or controls have significant grapheme–colour preferences?

For this analysis, we examined the letter–colour associations produced by Synaesthetes, Forced-choice controls and Free-choice controls. For each letter of the alphabet (e.g., *a*), and for each of the 11 category colour terms (e.g., red), a count was made for the number of responses representing that particular letter–colour combination. As an example, Figure 1 shows the frequency distribution of colours produced by our Synaesthete group for the letter *a*. It can be seen that *a* elicits the colour red above all others.

In order to investigate this statistically, we took an estimate of the probability that a given letter–colour combination could occur by chance. This was calculated using the colour probabilities derived from the corpus as a whole for each group. For example, the colour red accounted for 11% of the total number of synaesthetes' responses—so the probability that a given letter should be assigned the colour red (all things being equal) is .11. This was used as a baseline for calculating binomial probabilities (see Baron-Cohen et al., 1993; Ward & Simner, 2003). For example, 69 out of 70 synaesthetes produced a colour for the letter *a*, and 30 of these were red. Given the overall probability of choosing red (.11), this result is highly significant ($p < .001$). Thus we can conclude that the colour red is associated with the letter *a* for synaesthetes more often than we would expect by chance. Applying the same analysis to all letter and colour combinations reveals a set of significant letter–colour associations for each participant group. These are shown in Figures 2–4 (for Synaesthetes, Forced-choice controls, and Free-choice controls, respectively).

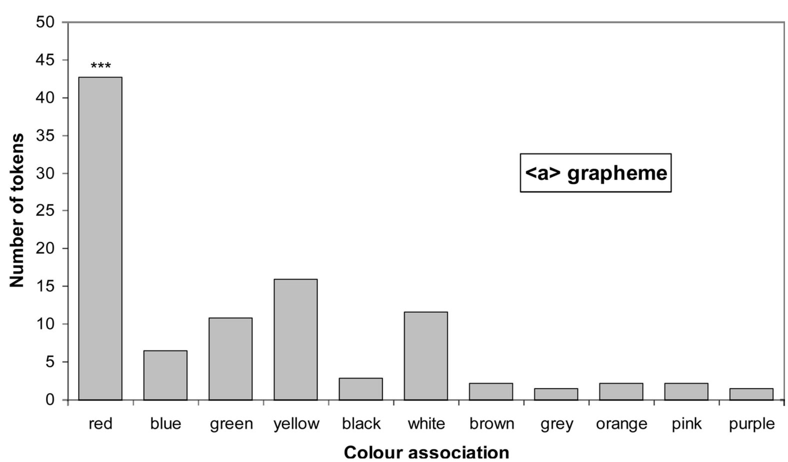

Figure 1. *Frequency distribution of colours for the grapheme ⟨a⟩. ***$p < .001$.*

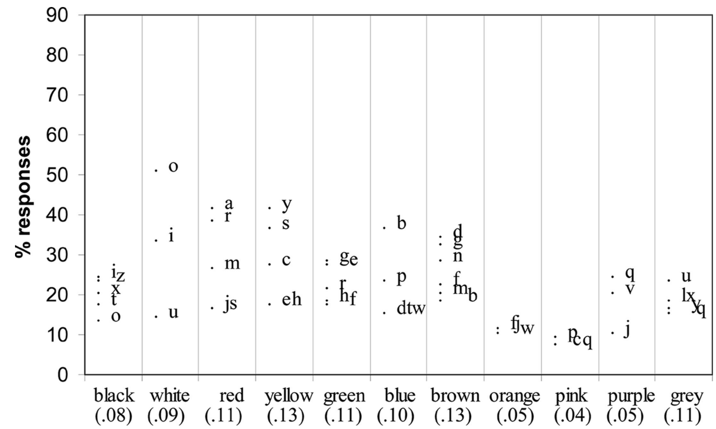

Figure 2. *Significant letter–colour combinations for Synaesthetes ($p < .05$). Figure shows percentage of responses for each (significant) letter that were of a given colour, with chance probabilities shown on the x-axis.*

The associations represented in Figures 2–4 are summarised by letter, in columns 2–4 of Table 1, and these letter–colour associations can be seen to provide the following information. First, they allow us to concur with researchers such as Baron-Cohen et al. (1993) and Day (2001, 2005) who suggested that synaesthetes may show significant group preferences for certain grapheme–colour associations. Like them, we found a significant tendency for the letter *i* to be white or black, for example, and we extend their findings by providing objective evidence for the genuineness of all our synaesthete cases.

Crucially, however, our findings show that non-synaesthetes, too, produce significant letter–colour associations. Moreover, such associations exist even in the Free-choice group, where participants were not *forced* to produce associations by the demands of the task. For example then, there is a tendency for the colour green to be paired with the letter *f*, in both these groups of non-synaesthetes. In other words, participants from

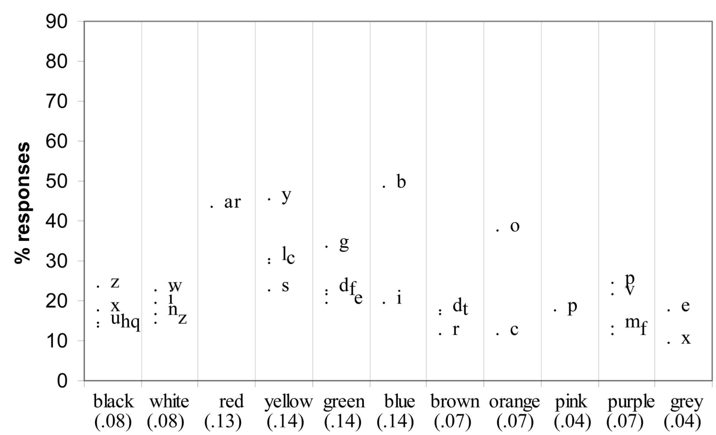

Figure 3. *Significant letter–colour combinations for Forced-choice controls ($p < .05$). Figure percentage of responses for each (significant) letter that were of a given colour, with chance probabilities shown on the x-axis.*

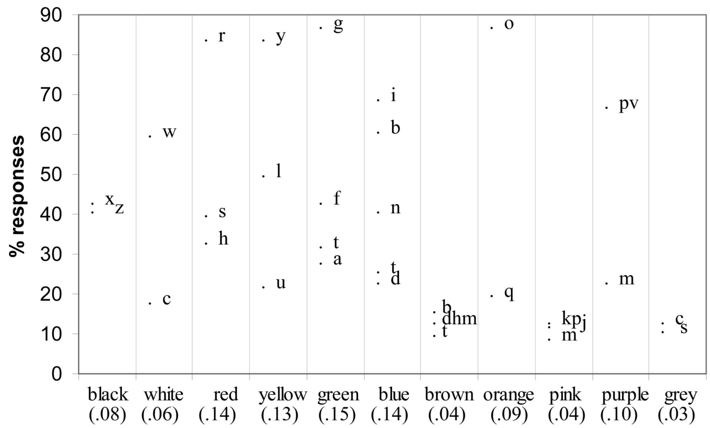

Figure 4. *Significant letter–colour combinations for Free-choice controls (p < .05). Figure shows percentage of responses for each (significant) letter that were of a given colour, with chance probabilities shown on the x-axis.*

the population at large associate the letter *f* with green (rather than, say, red, or yellow), and do so even if they are not obliged to state any association at all. Indeed, there are 16 letters for which both control groups share a significant colour association (which can be seen from a comparison of columns 3 and 4 in Table 1). In order to test whether this similarity arose by chance, we randomised the letter–colour pairings for our two groups of controls, and re-scored the number of matches between them. The number of chance matches (4) was significantly lower (Wilcoxon $Z = -4.0$, $p < .001$) suggesting that non-synaesthetes generate a similar set of significant letter–colour associations independently of task demands.

Are there between-group consistencies for synaesthetes and controls?

It seems clear from Table 1 that certain regularities are repeated between synaesthete and non-synaesthete participant groups. To assess this statistically, we made the same group-wise comparison described in the section above, but between synaesthete and non-synaesthete groups. The letter–colour associations of our synaesthetes match with 16 from the Forced-choice group, and 13 from the Free-choice group, and base-line scores were calculated (by randomising the associations) as 5 and 5 matches respectively. Wilcoxon tests show these differences from chance to be significant ($Z = -2.8$, $p < .01$; and $Z = -2.5$, $p < .05$, respectively). In other words, synaesthetes and controls produce significant similarities in their letter–colour associations, suggesting that both populations are driven by (at least some) shared underlying mechanisms. In the following sections, we examine these in more detail.

Underlying mechanisms of grapheme–colour correspondences

In this section we ask whether any underlying considerations can be found to account for the significant pattern of letter–colour associations in our groups of participants. We consider issues of methodology as well as cognitive and linguistic factors, and these are treated in turn below.

Methodological ordering and ease-of-generation. The norms of Battig and Montague (1969) indicate the ease-of-generation of colour terms, and were significantly correlated with the frequency with which colours were produced overall by our Free- and Forced-choice controls. However, these norms show not only that certain colours tend to be generated more often than others (e.g., red > purple) but also, that these

Table 1. *Significant letter colours for Synaesthetes and Forced-/Free-choice controls*

	Significant colour associations		
		Controls	
Letter	*Synaesthetes*	*Forced-choice*	*Free-choice*
a	red	red	green
b	blue, brown	blue	blue, brown
c	yellow, pink	yellow, orange	grey, white
d	brown, blue	brown, green	blue, brown
e	green, yellow	grey, green	
f	orange, brown, green	green, purple	green
g	green, brown	green	green
h	yellow, green	black	red, brown
i	white, black	white, blue	blue
j	purple, orange, red		pink
k			pink
l	grey	yellow	yellow
m	red, brown	purple	brown, purple, pink
n	brown	white	blue
o	white, black	orange	orange
p	blue, pink	purple, pink	purple, pink
q	purple, pink, grey	black	orange
r	red, green	red, brown	red
s	yellow, red	yellow	red, grey
t	black, blue	brown	blue, green, brown
u	grey, white	black	yellow
v	purple	purple	purple
w	orange, blue	white	white
x	black, grey	black, grey	black
y	yellow, grey	yellow	yellow
z	black	black, white	black

Note: $p < .05$.

prototypical colours tend to be generated earlier. It is important to consider, therefore, whether the apparent preference for certain grapheme–colour combinations found in our study is partially dependent on this ordering phenomenon. For example, the letter *a* may be reliably associated with the colour red simply because *a* appeared first in our list of (alphabetically ordered) letters, and red is an early-generated colour term. To test this, we coded each significant letter–colour association according to the alphabetical order of the letter (e.g., a = 1; b = 2) and the ranking of the colour in the Battig and Montague norms (e.g., blue = 1; red = 2). For example, the association of $a \rightarrow$ red was coded as 1 (alphabetically) $\rightarrow$ 2 (ease-of-generation). Rankings for alphabetical presentation and ease-of-generation were compared within each group, and a near-significant correlation was found for Forced-choice controls ($\rho = .353$, $p < .05$), but not for either Free-choice controls or synaesthetes. This suggests that, while Forced-choice controls were, to some extent, merely producing colours "off-the-cuff", according to the ease with which these colours can be generated in sequence, the remaining participants were not.[2]

We point out that the influence of ease-of-generation is not equivalent to a lexical frequency effect. The frequency with which colour terms are encountered in English can be seen by their occurrence in the British National Corpus (BNC), a collection of over 100 million words from both written and spoken British English. In this, our eleven colour terms are ranked in an order shown in the Appendix, but this ordering does not correlate with the Battig and Montague norms ($\rho = .073$, $p = ns$). Hence, the most common colour terms by frequency (e.g., black/white) are not those that might be considered 'prototypical' exemplars. In our data, there is no correlation between the lexical frequency of colour terms, and the order in which colours were produced for the alphabetical list of letters (either for synaesthetes or Forced-/Free-choice controls: all $|\rho|$'s $< .30$, ps $= ns$). We will return

[2] It is likely that control participants generate a list of candidate colours for each letter, with the candidate list ordered—at least to some extent—according to ease-of-generation. While Forced-choice controls are obliged to state a colour for every letter (working steadily through their candidate list) Free-choice controls are free to reject all candidates at any given point, and might even return to the top of the candidate list for the next selection. This may explain why Free-choice controls show an influence of ease-of-generation in the overall frequency of colours generated, without an effect of presentation order.

to this issue of frequency below, but first consider ordering effects of a different type.

Inherent ordering of semantic linear orders. In this section, we begin with an examination of the significant associations from our Randomised group, shown in Figure 5, and summarised in Table 2, column 2. A comparison of Tables 1 and 2 shows an apparent similarity between the letter–colour associations of Randomised controls and those of the comparable ordered group (Forced-choice controls). Indeed, this similarity was significantly higher than the number of matches found in the chance pairings of a scrambled list ($Z = -3.87$, $p < .001$). A significant similarity was found, also, between Randomised controls and our synaesthete group ($Z = -2.5$, $p < .02$), suggesting that the mechanisms that guide the generation of letter–colour associations are shared, to some extent, between synaesthetes and controls, notwithstanding presentation order. However, letters (and numerals, and days of the week etc.) have an *inherent* ordering that is independent of the order of presentation. Hence, the position of a letter within the alphabet or the ordinal position of a number may be the critical property that determines colour assignment, and we examine this possibility below.

We tested for the influence of inherent ordering in two ways. First, we examined the significant letter–colour associations of our Randomised group, and found no significant correlation ($\rho = .83$, $p = ns$) between inherent alphabetical ordering and our measure of colour typicality/ease-of-generation (from Battig & Montague, 1969). Second, we tested claims in Shanon (1982) who found that the order in which synaesthetic colours are assigned to numerals reflects the order in which colour terms are introduced into human languages, as described in the typology of Berlin and Kay (1969). Shanon (1982) found that this ordered typology (shown in the Appendix) predicted the number–colour associations for a group of self-reported synaesthetes, such that low numbers associated with early colour distinctions, and high number with later distinctions. However, Shanon suggests that a similar pattern might be less apparent for letters, since these are likely to be influenced instead by "linguistic associations: phonological, semantic, and pragmatic" (Shanon, 1982, p. 82). Our findings concur with Shanon to the extent that there is no correlation between the Berlin and Kay ordering, and the ordering (inherent or otherwise) of alphabetic colour associates for our synaesthetes, Forced-choice, Free-choice or Randomised control groups (all $|\rho|$'s < 2.6, ps $= ns$).

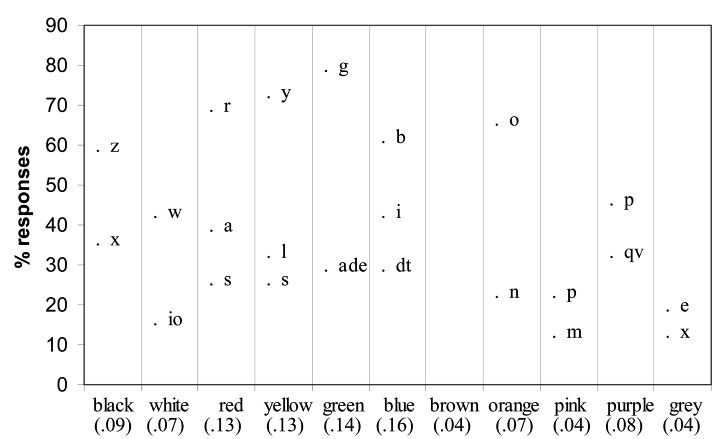

Figure 5. *Significant letter–colour combinations for Randomised controls ($p < .05$). Figure shows percentage of responses for each (significant) letter that were of a given colour, with chance probabilities shown on the x-axis.*

Table 2. *Significant letter colours for Randomised and German controls*

	Significant colour associations	
	Controls	
Letter	*Randomised*	*German*
a	red, green	red
b	blue	blue, brown
c		yellow
d	green, blue	green
e	grey, green	pink
f		purple, brown
g	green	green, grey
h		blue
i	blue, white	blue, yellow
j		green
k		red
l	yellow	purple, orange
m	pink	grey, blue
n	orange	grey, green
o	orange, white	yellow, orange
p	purple, pink	pink
q	purple	white
r	red	red
s	yellow, red	black, grey, yellow
t	blue	blue
u		blue, brown
v	purple	purple
w	white	white
x	black, grey	black
y	yellow	green
z	black	red, black

Note: $p < .05$.

It seems, then, that the key determinant of colour associations for letters is not to be found in the inherent ordering of the alphabet, neither with respect to ease-of-generation, nor with respect to the ordering of the Berlin and Kay typology.

Grapheme frequency. In the previous sections, we saw that presentation order plays a role in the generation of letter–colour correspondences for non-synaesthetes, but that it does not provide a complete explanation of their choices (since these are mirrored in randomised lists) and nor does it account for the associations made by synaesthetes. We saw, too, that inherent ordering failed to provide a satisfactory account, either in terms of colour typicality/ease-of-generation, or with respect to the Berlin and Kay typology. We question then whether there is some property of the grapheme itself, rather than its place in a presentation order, that influences the colour assigned to it. Above we examined the role of lexical frequency of colour terms, but graphemes, too, can be quantified in terms of their frequency in the English language. We ask then whether there is any evidence for the role of grapheme frequency in letter–colour associations, for either synaesthetes or controls.

We hypothesised one of three possible mechanisms for the role of grapheme frequency. First, participants might associate high frequency letters with high frequency colour terms. Second, they might associate high frequency letters with easy-to-generate colours (from Battig & Montague, 1969). Third, participants might associate high frequency graphemes with early-introduced colours (from the typology of Berlin & Kay, 1969). To test these hypotheses, letter frequencies were extracted from the BNC, and converted to rankings from highest to lowest (*e, t, a, o, i, n, s, r, h, l, d, c, u, m, f, p, g, w, y, b, v, k, x, j, q, z*). With Spearman's Rho tests of ranked correlation, we examined the influence of grapheme frequency for each group of participants, and for each of the hypothesised mechanisms.

For all groups of control participants (Forced-choice; Free-choice; Randomised) there was no significant relationship between grapheme frequency and any other factor hypothesised (all $|\rho|$'s $< .27$; ps $= ns$). In contrast, however, we found a significant influence of grapheme frequency in the letter–colour correspondences of synaesthetes. Although there was no correlation between grapheme frequency and ease-of-generation values ($\rho = .29$; $p = ns$) our remaining two hypotheses were supported. Grapheme and colour frequencies were positively correlated such that high frequencies graphemes are paired with high frequency colour terms ($\rho = .37$, $p < .02$). Additionally, grapheme frequency correlated with colours as they appear in the Berlin and Kay typology, such that high frequency graphemes were paired with the earliest colour distinctions ($\rho = .473$, $p < .01$).

Thus far, our findings suggest that synaesthetes and controls produce letter–colour associations with qualitatively different mechanisms. We saw above that controls generate colours in order through the list of letters, according to the ease with which they could produce colour terms. In contrast, synaesthetes are sensitive to the frequency of graphemes, and match high frequency graphemes with high frequency colour names, or with more fundamental colour distinctions.

Cross-linguistic comparisons. Above we saw that letter–colour associations are determined, in part, by characteristics of the grapheme. While some properties of an English letter are invariant across languages that share the same (Roman) alphabet (e.g., its shape, and position in the sequence) other properties change to a greater or lesser degree. Letter names are typically idiosyncratic (*y* = *wye* in English, but *yot* in German) and grapheme–phoneme correspondences, although less variable, can differ too (e.g., < w > = /v/ in German, but < w > = /w/ in English). In this section we examine the extent to which the language of the speaker influences the assignment of colours to graphemes. Since we do not have access to a large enough sample of synaesthetes from different language groups, we offer a preliminary comparison of English and German non-synaesthetes.

An analysis of the frequency and proportion of colours generated in our German control group reveals a set of significant letter–colour correspondences, and these are shown in Figure 6 below (and summarised in the final column of Table 2).

We compared the number of matches between our German controls and the comparable English group (Free-choice), and found similarities across groups that were greater than we would expect by chance ($Z = -2.3$, $p < .05$). These similarities (cf. Table 1 column 4, and Table 2 column 3) suggests that the two groups must have been operating under some shared mechanism(s). We pursued one line of questioning, which arose from an observation from the data. It appeared that where the two languages share similar colour terms, there was greater agreement on the letter trigger for that colour. For example, the colour term *white* is similar across languages (German: *weiss*) and both languages agree that *w*→white. In contrast, German and English have orthographically distinct colour terms for

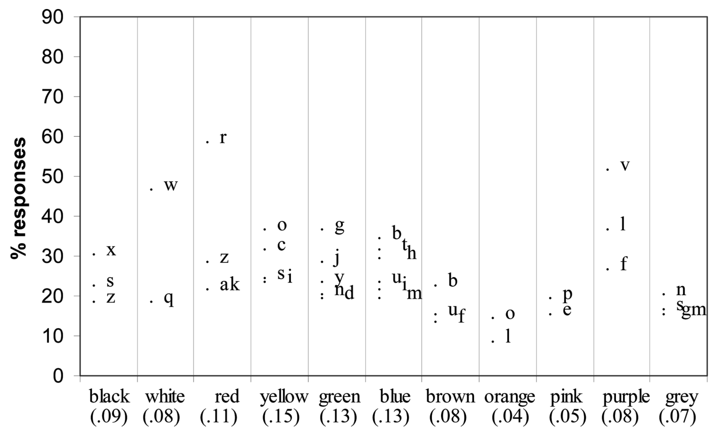

Figure 6. *Significant letter–colour combinations for German controls (p < .05). Figure shows percentage of responses for each (significant) letter that were of a given colour, with chance probabilities shown on the x-axis.*

purple (German: *lila*) and this colour is triggered by *p* in English, but *l* in German. This suggests the role of learned vocabulary knowledge in our non-synaesthetic groups, and we investigate this further in the section below. We ask not only whether quantitative evidence can be found for the influence of vocabulary knowledge on associations made by controls, but also whether this factor influences the synaesthetic population.

Vocabulary knowledge. Effects of vocabulary knowledge have been documented in cases of synaesthesia in which the elicited experience is taste. Ward and Simner (2003) show that synaesthetic tastes are triggered by phonemes, and that these phonemes also tend to appear in the name of the corresponding foodstuff (e.g, /ɪ/, /n/ and /s/ can trigger a taste of mince /mɪns/). In this section, we examine whether vocabulary knowledge also plays a role in grapheme−colour correspondences. Specifically, we examined whether there is evidence for initial letter priming, in which colours would tend to be paired with the initial letter of the colour term (e.g., *b*→blue). For this, we returned to the complete set of colour responses (e.g., crimson, blue, lime) for both synaesthetes and their (Forced-choice) controls. Each response was coded as either a "match", if the stimulus letter matched the initial letter of the colour name (e.g., *b*→blue) or a "mismatch" if it did not (e.g., *b*→pink). The mean number of matched responses per participant was 3.4 for controls and 2.0 for synaesthetes (*SD*s = 2.2 and 1.4, respectively). To determine whether these figures were significantly higher than chance levels, we generated base-line values by re-calculating the correspondence scores after randomising each subject's responses to their 26 letters. This gave base-line means of 0.92 for controls, and 0.90 for synaesthetes. These values were examined in paired-sample *t*-tests for each group. Controls showed a significant difference between ordered and base-line lists, both by subjects, $t_1(61) = 8.63$, $p < .001$, and by items, $t_2(25) = 3.55$, $p < .01$, and the same effect was found for synaesthetes, $t_1(69) = 6.2$, $p < .001$; $t_2(25) = 2.8$, $p < .01$. This suggests that both synaesthetes and non-synaesthetes generate colour responses in which the stimulus letter tends to match the initial letter of the colour term (e.g., *b*→blue).

To determine whether synaesthetes are more or less influenced by learned vocabulary knowledge compared to controls, we collapsed all findings into a two-way ANOVA (mixed design by subjects, and paired design by items). There were significantly more matches in the ordered data compared to the base-line data, $F_1(1) = 117.5$, $p < .001$; $F_2(1) = 15.6$, $p < .01$, and this was modified by an interaction with participant group, $F_1(1) = 17.0$, $p < .001$; $F_2(1) = 3.2$, $p < .09$. Hence synaesthetes were less likely to be influenced by the stimulus letter in their choice of colours, compared to controls. The lower by-items significance in our interaction suggests that vocabulary-influenced colours are more likely for some letters than others (e.g., for synaesthetes, *b* tends to elicit blue but *o* does not tend to elicit orange).

GENERAL DISCUSSION

Our analyses have shown that significant associations exist between letters and colours, in both synaesthetic and non-synaesthetic populations. Significant correspondences were found in each of five participant groups, which varied according to participant population and experimental procedure. Like Day (2001, 2005) and Baron-Cohen et al. (1993) we found non-random patterns in the letter−colour associations of synaesthetes, suggesting that their responses, while often wide-ranging and superficially diverse, are nonetheless structured. Unlike Day, Baron-Cohen and colleagues, we do not examine historical cases, and accompany our findings with objective evidence that all our synaesthete cases are genuine. We show, too, that significant letter−colour correspondences exist also in the non-synaesthetic groups, and we examined the underlying principles that dictate the choice of associations for both populations.

Synaesthetes tend to pair high frequency graphemes with high frequency colour names, and are sensitive, too, to the typology of Berlin and Kay (1969). This reflects the order in which colours are introduced into human languages, and may also indicate the order in which colour distinctions are acquired in language development (but see Pitchford & Mullen, 2002). Synaesthetes incorporate this attribute in their associations, since high frequency graphemes tend to associate with the more fundamental colour distinctions.

Non-synaesthetes were insensitive to grapheme frequency, colour frequency, and the Berlin and Kay typology. Instead, their decisions were driven to some extent by the sequential ordering of materials, and the ranking of colours in the Battig and Montague norms. These norms represent the ease and ordering with which colours can be generated on demand, and provide an index of exemplar-typicality. For non-synaesthetes, letters presented early in testing are paired with more "typical" colours. This factor has no influence on synaesthetes, suggesting that their correspondences were not generated "off-the-cuff" by the demands of our task. Additionally, synaesthetes used a significantly broader and more detailed set of colour terms in their descriptions, which may also suggest a less superficial component to their associations.

The letter–colour pairings of our control groups differ from those of synaesthetes in terms of consistency, automaticity, and phenomenology, but certain patterns of responses appear to be common to both synaesthetes and non-synaesthetes alike. Such similarities between populations suggested that grapheme–colour synaesthesia, like the music–colour variant, may stem from an exaggeration of mechanisms for cross-modal association that are common to us all. Both populations are influenced by linguistic priming, in that colours tend to be paired with the initial letter of the colour name (e.g., *b*→*b*lue), although this effect was more dominant in non-synaesthetes. An influence of learned vocabulary terms has also been found in other forms of synaesthesia (e.g., the lexical–gustatory variant; Ward & Simner, 2003) although this is the first evidence of this type in the colour domain.

Marks (1975), too, proposed principles for the assignment of colours to letters in synaesthesia, although he limited the focus of his study to phonological vowels. He suggests that the light/darkness of the colour was predicted by the pitch of the vowel, and the red/greenness by the ratio of second and third formants. However, to the extent that our data can be compared with Marks (1975), our significant correspondences only partially correspond. Marks (1975) noted that /a/ tended to be red and blue (we find *a* to red alone), /e/ (or /ɛ/) tended to be yellow (we find *e* to be green then yellow), /i/ (or /ɪ/) tends to be white (we find *i* to be white and black), /o/ tends to be red and black (we find *o* to be white then black) and /u/ (or /ʊ/ or /ɤ/) tends to be blue, brown and black (we find *u* to be grey then white). There are several differences between our studies, however, that would account for any discrepant findings. Marks based his investigation on cases in the historical literature (which lack independent verification of genuineness) and his reports of predominant letter–colour associations were not accompanied by tests of significance. Additionally, the heterogeneous linguistic backgrounds of his participants (many of whom were French and German) are likely to have influenced responses. Finally, it is simply unclear whether meaningful comparisons can be made between an analysis of phonological vowels and our own study of grapheme–colour pairings, given the lack of one to one correspondence between letters and phonemes, both within English and across languages.

While our study reveals a number of biasing influences in the association of letters to colours, it does not offer a full account at a letter-by-letter level. For example, the fact that *a* tends to be red and *w* tends to be orange for synaesthetes may relate to the different frequencies of these graphemes and colour terms, but this does not explain why *w* should tend to be orange as opposed to, say, purple (another low frequency colour term) or why *a* should be more likely to be red than green. Equally, while some non-synaesthetes' preferences are relatively transparent (e.g., the "off-the-cuff" pairings of easy-to-generate colours with early-presented stimuli, or the more enduring preferences for initial-letter matches such as w→white) other associations are more intriguing. These are the significant preferences that cannot be attributed to linguistic priming (e.g., s→yellow, z→black) *nor* to ease-of-generation (because they remain even for the group that saw letters in a series of repeatedly randomised orders). It is probable, then, that other sources of bias exist which are yet unknown (see Day, 2005, for possible suggestions; e.g., relating to the geometric shape of letters).

However, our findings might nonetheless inform theories concerning the genesis of grapheme–colour synaesthesia. First, our data show that the colour of graphemes can be strongly influenced by environmental biases. These include the frequency of graphemes in the linguistic environment and the learned (arbitrary) names that we use to denote colour categories. It is interesting, also, that stimulus frequency and lexical knowledge have been found to exert strong influences in at least one other type of synaesthesia, namely the lexical–gustatory variant (Ward & Simner, 2003; Ward et al., 2005). This suggests that synaesthesia can arise from an interaction between genetic predisposition (e.g., Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996) and environmental influences, perhaps at key stages of language development (e.g., during the acquisition of colour terms).

Our study of synaesthesia has wider implications for understanding the development of perceptual systems, and the interplay between perceptual and non-perceptual systems more generally. Neuropsychological studies have investigated the ways in which perceptual systems such as the organisation of colour space may be influenced by linguistic knowledge (for a review, see Davidoff, 2001). Our research on grapheme–colour synaesthesia makes contact with this debate by showing that the linguistic composition of colour terms (e.g., the word-initial letter) can have direct repercussions within the visual perceptual system. For synaesthetes, letters tend to trigger the perception of colour via initial letter priming (*b* triggers blue) and this can be traced back to patterns in the non-synaesthetic population, who make cognitive but non-perceptual associations by the same process.

Previous studies have described cases of acquired synaesthesia in neuropsychological patients (e.g., Vike, Jabbari, & Maitland, 1984) and one interesting observation is that there seem to be no examples of the grapheme–colour variety. This omission might suggest an important difference between acquired and developmental patterns. While developmental synaesthesia may shape itself to knowledge learned (e.g., letters/numbers; and our study sheds light on the possible cognitive mechanisms by which this may occur) acquired synaesthesia may be less inclined to do so. Hence, although the grapheme–colour associations of developmental synaesthetes are shared, in part, by non-synaesthetic adults, the cognitive associations of these latter fail to take on a perceptual characteristic after organic neural damage. This suggests in turn that mature grapheme centres are no longer vulnerable to cross-modal association once conceptual/linguistic structures have been put in place.

We have shown that synaesthesia relies on certain cognitive processes that are common to the normal population, but also on those *not* found in the population at large. The fact that synaesthesia shows *different* patterns of processing provides evidence that synaesthesia is more than simply the extension of a normally occurring mode of experience. Conversely, the fact that certain processing is *shared* by non-synaesthetes shows that the normal population, too, use non-random binding processes to associate colours with learned abstract visual symbols. Moreover, this same fact shows also that developmental synaesthetes recruit existing cognitive machinery, albeit applied it in a way that produces a perceptual association in place of a cognitive one.

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APPENDIX

Ranking (descending) of 11 basic colour terms in terms of ease/order of generation norms, colour name frequency and order of entry into human languages

Ease/order of generation (Battig & Montague, 1969)	*Colour name frequency (British National Corpus)*	*Entry into language (Berlin & Kay, 1969)*
blue	black	black/white
red	white	red
green	red	green/yellow
yellow	green	blue
orange	brown	brown
black	grey	orange/purple/grey/pink
purple	yellow	
white	pink	
pink	orange	
brown	blue	
grey	purple	