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Language use statistics and prototypical grapheme colours predict synaesthetes' and non-synaesthetes' word-colour associations

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ABSTRACT

Synaesthesia is the neuropsychological phenomenon in which individuals experience unusual sensory associations, such as experiencing particular colours in response to particular words. While it was once thought the particular pairings between stimuli were arbitrary and idiosyncratic to particular synaesthetes, there is now growing evidence for a systematic psycholinguistic basis to the associations. Here we sought to assess the explanatory value of quantifiable lexical association measures (via latent semantic analysis; LSA) in the pairings observed between words and colours in synaesthesia. To test this, we had synaesthetes report the particular colours they experienced in response to given concept words, and found that language association between the concept and colour words provided highly reliable predictors of the reported pairings. These results provide convergent evidence for a psycholinguistic basis to synaesthesia, but in a novel way, showing that exposure to particular patterns of associations in language can predict the formation of particular synaesthetic lexical-colour associations. Consistent with previous research, the prototypical synaesthetic colour for the first letter of the word also played a role in shaping the colour for the whole word, and this effect also interacted with language association, such that the effect of the colour for the first letter was stronger as the association between the concept word and the colour word in language increased. Moreover, when a group of non-synaesthetes were asked what colours they associated with the concept words, they produced very similar reports to the synaesthetes that were predicted by both language association and prototypical synaesthetic colour for the first letter of the word. This points to a shared linguistic experience generating the associations for both groups.

1. Introduction

Synaesthesia is the neuropsychological phenomenon in which certain individuals have unusual sensory associations, such as seeing particular colours in response to particular words, associating shapes with tastes, or experiencing smells in response to sounds (Galton, 1880; Jones et al., 2011; Mattingley, Rich, Yelland, & Bradshaw, 2001; Ramachandran & Hubbard, 2001; Simner, Glover, & Mowat, 2006a). While it was previously thought that the particular associations observed were arbitrary and idiosyncratic to particular synaesthetes, growing evidence suggests that there is some systematicity to the associations, grounded in associative and psycholinguistic processes. For example, it has been shown that high-frequency graphemes tend be associated with high-frequency colours (e.g., *a* is more commonly associated with *red* than with other colours), whereas low-frequency graphemes tend to be associated with low-frequency colours (e.g., *q* is more commonly associated with *purple* than with other colours) (Rich, Bradshaw, & Mattingley, 2005; Simner, 2007; Simner et al., 2006a; Simner et al., 2005). Here we studied lexical-colour synaesthesia, which allowed us to go beyond a simple frequency analysis such as that done with the grapheme-colour synaesthetes, and focus on the extent to which two words co-occur in language contributes to concept-colour pairings. More specifically, the aim of this paper was to test whether language *co-occurrence* statistics, the degree to which a concept co-occurs with words that denote perceptual experience, could predict the particular lexical-colour associations reported by synaesthetes.

Synaesthesia is characterised by unusually dense and diffuse neural connections (Bargary & Mitchell, 2008). One theory proposes that synchronous firing of cells representing the inducer (e.g., the word) and the concurrent (e.g., the colour) is integral to the development of synaesthetic associations (Brang, Hubbard, Coulson, Huang, & Ramachandran, 2010; Brang, Rouw, Ramachandran, & Coulson, 2011). The brain regions that process and represent visual form (including letters and words) and those which encode colour are adjacent to one another. This, coupled with the synaesthetes' enhanced neural connectivity, presents ample opportunity for such synchronous firing to occur and to solidify neural links between linguistic inducers and

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colour concurrents. It is perhaps unsurprising, therefore, that lexical-colour (in particular, weekday-colour) is among the most commonly experienced variants of synaesthesia (Simner et al., 2006b). Furthermore, some colours appear to have conceptual links in language: *feeling a little blue*, or *green with envy*. One possibility, therefore, is that the frequent co-occurrence of concepts and colours in the ambient language influence the specific word-colour association that synaesthetes develop. Such associations in language could create new or strengthen existing synaesthetic associations between words and colours via their repeated co-activation. Here we sought to test the influence of language association on the manifestation of adult synaesthetic associations for concept words.

In a related domain, it has been well documented that there is a general human tendency to map concepts in space. For example, we refer to a person who is happy as *up*, or someone who is sad as *down*. This suggests that emotional valence has a vertical mapping in space. Moreover, we describe looking *forward* to tomorrow and *back* in time, again implicating a directional component to mental representations of time (Boroditsky, Fuhrman, & McCormick, 2011; Santiago, Lupianez, Perez, & Funes, 2007; Weger & Pratt, 2008). Such mental representations are often measured in the laboratory via *conceptual cueing*, which refers to the tendency for participants to respond more efficiently (quickly and accurately) to visual stimuli in particular spatial locations after being presented with particular concept words. For example, participants are quicker to respond to visual stimuli in the top part of the screen after the word *sun* or *happy*, and quicker to respond to visual stimuli in the bottom part of the screen after the word *grass*, or *sad* (Chasteen, Burdzy, & Pratt, 2010; Dudschig, Souman, Lachmair, de la Vega, & Kaup, 2013; Estes, Verges, & Adelman, 2015; Estes, Verges, & Barsalou, 2008; Gozli, Chasteen, & Pratt, 2013; Gozli, Chow, Chasteen, & Pratt, 2013b; Meier & Robinson, 2004; Zwaan & Yaxley, 2003). A growing body of work indicates that language association statistics predict the manifestation of particular spatial mappings of concepts (Goodhew, McGaw, & Kidd, 2014; Hutchinson & Louwerse, 2013; Louwerse, 2008; Louwerse & Jeuniaux, 2010). Specifically, this means that the systematic co-occurrence of the words *happy* and *up*, for example, predict the upward shift of attention produced by the word *happy*. This has led to the suggestion that language association may actually causally create conceptual cueing (Goodhew et al., 2014). It is possible that such linguistically-based conceptual cueing effects could belong to a broader category of examples of how specific associations between stimuli derive from language exposure. From this perspective, we predicted that the specific perceptual mappings between inducers (words) and concurrents (colours) that synaesthetes experience would also be explained by systematic biases embedded in language. For example, synaesthetes might be more likely to see the word *sorrow* as blue if *sorrow* and *blue* co-occur frequently together in language.

The current study tested this possibility. Specifically, we assessed whether language co-occurrence statistics could explain the particular lexical-colour associations observed. We asked synaesthetes to report their colour experience in response to a standard set of conceptual cue items (Goodhew & Kidd, 2016). This stimulus choice was made because if synaesthetic perceptual experiences are influenced by language, then words with stronger conceptual meaning (e.g., *bliss*, rather than *Wednesday*), which have been shown to have systematic associations with other perceptual dimensions (i.e., space), should be most conducive to revealing such an association. If language association between these concept words and colour words can predict the pairings for synaesthetes, then this supports this hypothesis that language can shape the manifestation of a broad array of human perceptual and cognitive mechanisms.

2. Experiment 1A

The purpose of Experiment 1A was to examine whether language association statistics could predict the specific word-colour pairings that synaesthetes reports.

2.1. Method

2.1.1. Participants

Thirty synaesthetes were recruited via online, newsletter, and newspaper advertisements and word-of-mouth. Their mean age was 30.6 years (SD = 15.2), and 25 were female and 5 male. Three reported being left-handed, and the other 27 right-handed. All participants provided written informed consent prior to participation.

All of the synaesthetes completed the online battery (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) to verify their self-reported experiences of synaesthesia. Note that either grapheme-colour or lexical-colour synaesthetes could experience colours in response to the conceptual cues. The battery does not have a broader category to identify lexical-colour synaesthetes, but instead seeks to identify the more common variants, such as those who experience colour in response to days of the week (e.g., *Tuesday* is orange), or months of the year (e.g., *January* is yellow). However, there is evidence that such forms of synaesthesia, which are the most common forms, relate to what could be considered 'overlearned' sequences (Barnett, Feeney, Gormley, & Newell, 2009; Novich, Cheng, & Eagleman, 2011), and can occur in the absence of other forms of synaesthesia (Simner et al., 2006b). In contrast, grapheme-colour synaesthesia is more likely to be related to lexical-colour synaesthesia. We were interested in synaesthetic colours elicited in response to the concept words. For this reason, we required participants to be verifiable grapheme-colour synaesthetes, and then explicitly asked synaesthetes what colours they experience or associate with a range of concepts, if any.

Specifically, we included for analysis synaesthetes who successfully passed the letter-colour subtest of the battery. Nineteen of the thirty self-reported synaesthetes met this classification requirement. All of these 19 synaesthetes had letter-colour consistency scores between 0 and 1.4 (M = 0.68, SD = 0.22), which is the range indicative of synaesthesia (Rothen, Seth, Witzel, & Ward, 2013). Appendix 1 provides comprehensive details on the forms of synaesthesia experienced by each participant.

2.1.2. Apparatus and materials

We sought to select target word stimuli that had strong and clear conceptual meanings and thus would have the greatest possibility of being systematically associated with colour words in language. Moreover, we reasoned that words that had clear and strong associations with another well-documented perceptual domain (i.e., vertical space) would be most likely to have such clear meaning and thus also be systematically associated with synaesthetic colours. Therefore, the words were selected from the recently-developed database of systematically rated items, called the *Conceptual Cueing Database* (Goodhew & Kidd, 2016). Specifically, we selected 24 items with the most consistent *up* and *down* association ratings in the database, with the constraint that the items selected equally represented abstract and concrete items. Items associated with down had ratings between −0.98 and −1, whereas positive items all had perfect +1 ratings. (This means that 98% and 100% of the participants involved in the rating validation study indicated that these items were associated with *down*, and 100% of the participants indicated that items were associated with *up*, respectively). All 24 selected items can be seen in Table 1.

2.1.3. Procedure

Synaesthetes were tested individually. They completed the synaesthesia battery on a laptop computer, and then completed a custom paper inventory that listed the 24 conceptual cue items on the left with space on the right for them to describe in writing the colours that they experienced in response to the items. They were asked to leave items blank if they did not experience a colour for that particular cue.

Table 1
The 24 conceptual cues selected for the presented study from the conceptual cueing database (Goodhew & Kidd, 2016).

Cues associated with *up*	Cues associated with *down*
Bliss	Unhappy
Cheerful	Sorrow
Happy	Negative
Joy	Miserable
Victory	Doom
Positive	Bleak
Aircraft	Underground
Genius	Underworld
Peak	Grave
Sun	Mud
Star	Trash
Tower	Puddle

Table 3
Synaesthetes' most frequently-reported colour in response to each of the concept words.

Concept word	Most frequently associated colour
Bliss	Pale blue
Cheerful	Yellow
Happy	Yellow
Joy	Yellow
Victory	White/red
Positive	Red/white
Aircraft	Red
Genius	Green
Peak	Yellow/green/orange/blue
Sun	Yellow
Star	Yellow
Tower	Yellow/blue
Unhappy	Yellow
Sorrow	Blue
Negative	Yellow/brown
Miserable	Blue
Doom	Black
Bleak	Grey
Underground	Brown
Underworld	Brown
Grave	Grey/brown/green
Mud	Brown
Trash	Green
Puddle	Brown

2.2. Results

In order to test whether patterns of language use could explain the specific concept-colour associations observed in our synaesthetes, we sought to compare synaesthetes' reported concept-colour pairings against language co-occurrence statistics. Synaesthetes' reported colour associations can be seen in Table 2, and from this it can be seen that there does appear to be some systematic clustering. Table 3 shows the most commonly selected colour for each item. In the tables we show absolute frequencies (i.e., the number of synaesthetes reporting each given association), however, for the purpose of analysis, these were converted to proportions of responses per colour. For example, since there were 109 total yellow associations, the 16 synaesthetes identifying *cheerful* as yellow would be a proportion of 0.15 (or 15%).

2.2.1. LSA

We used latent semantic analysis (LSA) to quantify the associations between the concept and colour in language. LSA is a technique developed in computational linguistics, whereby words that regularly occur close together in speech and text are statistically grouped, under the assumption that words that commonly occur adjacent or nearly adjacent to one another are close in meaning. It employs singular value decomposition to provide a metric of the relationship or similarity of meaning between concepts, which disregards word order and syntactic structure (Dumais, 2005; Landauer, Foltz, & Darrell, 1998). The higher the value it produces the more frequently the two concepts are likely to occur together. Here, therefore, we used LSA similarity scores as a way of quantifying the association in language between the concept and colour words. Similarity scores (which range between −1 and +1) were obtained from the LSA pairwise comparison in term-to-term space. The topic space selected was general reading up

Table 2
The frequency of report of each colour for each of the conceptual cues made by the synaesthetes. Note that not all synaesthetes identified colours for all items, and some synaesthetes identified multiple colours for each item. That is, sometimes multiple distinct colours were listed (e.g., *black*, *white*), whereas sometimes colours that crossed category boundaries were listed (e.g., *blue-grey*), in which case both *blue* and *grey* would be scored. Furthermore, since we were interested in consistencies and systematic tendencies, a number of categorisation decisions needed to be made in order to constrain the number of categories to a reasonable number (e.g., *dark blue* was deemed to be sufficiently synonymous with *navy* to belong with this category rather than warrant its own individual category). The full list of categorisation decisions can be found in Appendix 2. Also note that in calculating the LSA scores and frequencies, we used the American spelling of *gray*, as this is the most common usage.

	Cream	Yellow	Green	White	Brown	Orange	Black	Pale blue	Purple	Blue	Grey	Silver	Dark grey	Red	Dark blue	Gold	Dark red	Pink
Bliss		3	2	4		1	1	5	2	2	1			2	1			4
Cheerful		16	3	3		3				2				2			1	2
Happy		9	4	1		3	1			3				5		1		1
Joy		6	4	3		4		1	2	3				3		2		1
Victory		4	1	5	2	1	2		3		2	1		5	2		1	1
Positive		2	1	4		1	2	1	1	3				5				1
Aircraft		2	3	3		1	1	2	1	4	2			5	1			
Genius	1	3	9	2	4		3		2	2	2	1		2		1		1
Peak		5	4	1	1	4	2		2	4	1			2	1			2
Sun		13	1		1	2	2			1				4		1		1
Star		7	1	5		3	3			5		2		2	1			2
Tower	1	5	3	2	3	1	2	1	2	5	4							
Unhappy		5	4		4	1	1		1	4	5		1	1	1			1
Sorrow		4	1	2	2		3			6	2		2	3	3		1	1
Negative	2	4	3	1	4	1	6			2	3	1		4			1	2
Miserable	1	1	2	2	4	2	3		1	5	2		1	2	3		2	1
Doom		1		2	5	1	10		1	3	2			1	2		2	
Bleak	1	3	3	2	1	1	1	1	2	5	7			1	1			2
Underground	1	3	4	1	11		4		1	1	2		1	1	1			1
Underworld	1	3	3	1	6					3	2			1	2		1	1
Grave		2	6		6		2		2	2	8	1	1		1			
Mud		1	2		14	1	1			1				1	1		2	1
Trash	1	4	6				2		1	3	3		1		1		1	1
Puddle	2	3	4		12	1	1		2	4	2			1	2			

to a 1-year college level, using the maximum number of factors available (see http://lsa.colorado.edu/).

2.2.2. Additional variables

Several control measures were included for the concept word cues, so as to mitigate against the possibility that any relationship between LSA scores and participants' concept-colour matching could be explained by simple properties of the concept word only. These variables were: (i) (log transformed) word frequency, (ii) imageability, and (iii) age of acquisition. Log transformed concept word frequency was calculated using Google Ngram (Michel et al., 2011), which is large, publicly searchable corpus. We set Google Ngram to calculate the (case-insensitive) concept frequencies over the most recent 10 years available from the database (1998–2008), with a smoothing of 10 to yield the average collocation across the 10 most recent years of the corpus. The log frequencies of each of the concept words can be found in Appendix 4. Imageablity (i.e., the degree to which a word is rated as concrete or abstract) ratings were taken from (Brysbaert, Warriner, & Kuperman, 2014). Age of acquisition ratings were taken from (Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012).

Finally, we also wanted to analyse how the prototypical grapheme-colour pairings that grapheme-colour synaesthetes experience may have influenced concept-colour pairings. That is, as mentioned earlier, there are prototypical colours that grapheme-colour synaesthetes see for given letters (e.g., *a* is *red*, *b* is *blue* or *brown*, *c* is *yellow* or *pink*, etc.) (Simner, 2007). It is possible that our participants' concept-colour pairings could be influenced by these pairings (e.g., the fact that *c* is typically *yellow* could have led to the word *cheerful* being associated with yellow most often). To test for this, we included a variable that coded for congruency between a given concept-colour association and the prototypical colour for the first letter of the concept word. For example, this means that the cheerful-yellow association would be coded as congruent (because *c* is typically yellow), whereas the sorrow-blue association would be coded as incongruent (because *s* is typically red or yellow, not blue).

2.2.3. Analysis

To examine whether language-use predicted the frequency with which synaesthetes selected particular colours as associated with given concept words, we firstly selected for analysis the colour dimensions which had 10 or more responses associated with them. That is, there were 10 or more responses that identified this colour as associated with given concept words. These were: yellow, green, white, brown, orange, black, purple, blue, grey, red, navy, and pink (whereas cream, pale blue, silver, dark grey, gold, and dark red were excluded). This cut-off was applied to ensure that there was sufficient variation along the colours included in the analysis, and had the secondary benefit of excluding six colours which are absent from the prototypical grapheme-colour alphabet. We aimed to test whether LSA statistics predicted participants' concept-colour associations controlling for the frequency, age of acquisition, and imageability of the concept words, and lexical-colour synaesthetes' prototypical grapheme-colour associations. We analysed the data using linear mixed effects modelling in R (version 3.2.2 R Development CoreTeam), which were calculated using the *lme4* package (version 1.1-8, Bates & Maechler, 2010). LSA, log transformed concept word frequencies, age of acquisition, concreteness, and first-letter prototypical colour congruency were fixed effects, and word and reported colour were random effects. Simple bivariate correlations between the continuous variables are reported in Appendix 5. All continuous variables were zero-centred to reduce any effect of collinearity. All variables were normally distributed, except for age of acquisition. Efforts to transform this variable proved futile, and so the raw values were retained for the analysis. Grapheme-colour congruency was sum coded (congruent $= 0.5$, incongruent $= -0.05$) to allow ANOVA-like interpretations of effects (Linck & Cunnings, 2015). Because the dependent measure was proportion we transformed it using a logit transformation (i.e., $y' = \ln[(y + c)/(1 - y)]$), where ln is natural logarithm, y represents the original DV value, and c represents a constant added to account for zero values.[1]

Since we had five independent variables and only 288 observations we had to be conservative in our statistical modelling. Our hypothesis was that LSA estimates of concept-colour association would predict participants' ratings, but grapheme-colour congruency has also been shown to predict synaesthetes' perceptual experiences. We therefore entered the factorial combination of these two variables into the model (i.e., main effects and their interaction), but only entered the remaining control variables as main effects. Random intercepts for concept and colour were included to control for by-colour and by-concept variability. Following Barr, Levy, Scheepers, and Tily (2013) we specified a maximal random effects structure.[2] The full maximal model failed to converge. Random slopes were removed one at a time; however, the model only converged when all were removed. Table 4 reports the results from the analysis.

Table 4 shows three notable results. Firstly, as predicted, LSA positively predicted synaesthete's concept-colour matchings, such that higher associations between a concept and a colour as measured by LSA predicted higher concept-colour matching by participants. Secondly, grapheme-colour congruency also predicted concept-colour matching, such that synaesthetes were more likely to choose colours for concepts based on biases deriving from the concept's first letter. Thirdly, there was a significant LSA by grapheme colour congruency interaction. This interaction is plotted in Fig. 1A, showing that the effect of grapheme-colour congruency becomes larger as LSA colour-concept estimates become larger. Finally, there was a significant effect of age of acquisition, which showed that concept-colour matchings became stronger with later acquired words.

2.3. Discussion

As hypothesised, the results revealed that language-association scores (as operationalised by LSA) significantly predicted synaesthetes' reports of their concept-colour associations. This means that systematic semantic association between a concept word (e.g., *sorrow*) and a colour word (e.g., *blue*) predicted the colour that participants reported in response to the concept words (e.g., sorrow = blue). Furthermore, consistent with previous research, the prototypical synaesthetic colour for the first letter of each concept word also influenced the colours that synaesthetes reported in response to the concept words. This means, for example, that the fact that the letter ‘s’ is often yellow for grapheme-colour synaesthetes predicted the fact that participants reported the colour yellow in response to words such as *sun* and *star*. These two variables also interacted, which means that whether or not the colour reported for particular concept words was predicted by the relationship between the first letter of the word and the prototypical grapheme-colour alphabet depended on the association in language between the given concept and colour word. The nature of this relationship was such that the effect of grapheme-colour congruency increased as LSA scores increased. Age of acquisition was also a reliable predictor of concept-colour pairings in its own right, further supporting the notion that language exposure creates reliable systematicities in concept-colour pairings. In Experiment 1B, we sought to examine whether non-synaesthete controls would report similar or different concept-colour associations.

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[1] Results did not change when the data were analysed using the transformed or untransformed data.

[2] In this instance, maximal structure meant random slopes for all fixed effects, but not the interaction between LSA and Grapheme-Colour Congruency, since the latter is a between-item variable.

Table 4
Liner mixed effects models predicting synaesthetes' concept-colour frequency reports. *$p < 0.05$. For model code see Appendix 6.

	β	SE(β)	*t*
Intercept	0.08	0.004	18.45
LSA	0.102	0.047	2.16*
Grapheme-colour congruency	0.04	0.011	3.3*
Log frequency	0.001	0.008	0.08
Age of acquisition	0.004	0.002	2.01*
Imageability	−0.0007	0.004	−0.19
LSA ∗ Grapheme-colour congruency	0.34	0.14	2.40*

3. Experiment 1B

The purpose of Experiment 1B was to assess the concept-colour associations reported by non-synaesthete controls. In previous research, it has been shown that when non-synaesthetes are asked to generate representative colours for graphemes, the colours they choose tends to mimic synaesthetes' perceptual experience of colour in response to graphemes, such as *y* being yellow, and *d* being brown (Rich et al., 2005; Simner et al., 2005). This suggests that early learning experiences common to both synaesthetes and non-synaesthetes shape these associations, but that the association has a distinct perceptual nature for synaesthetes (Rich et al., 2005). Here we wanted to see whether such similarities across

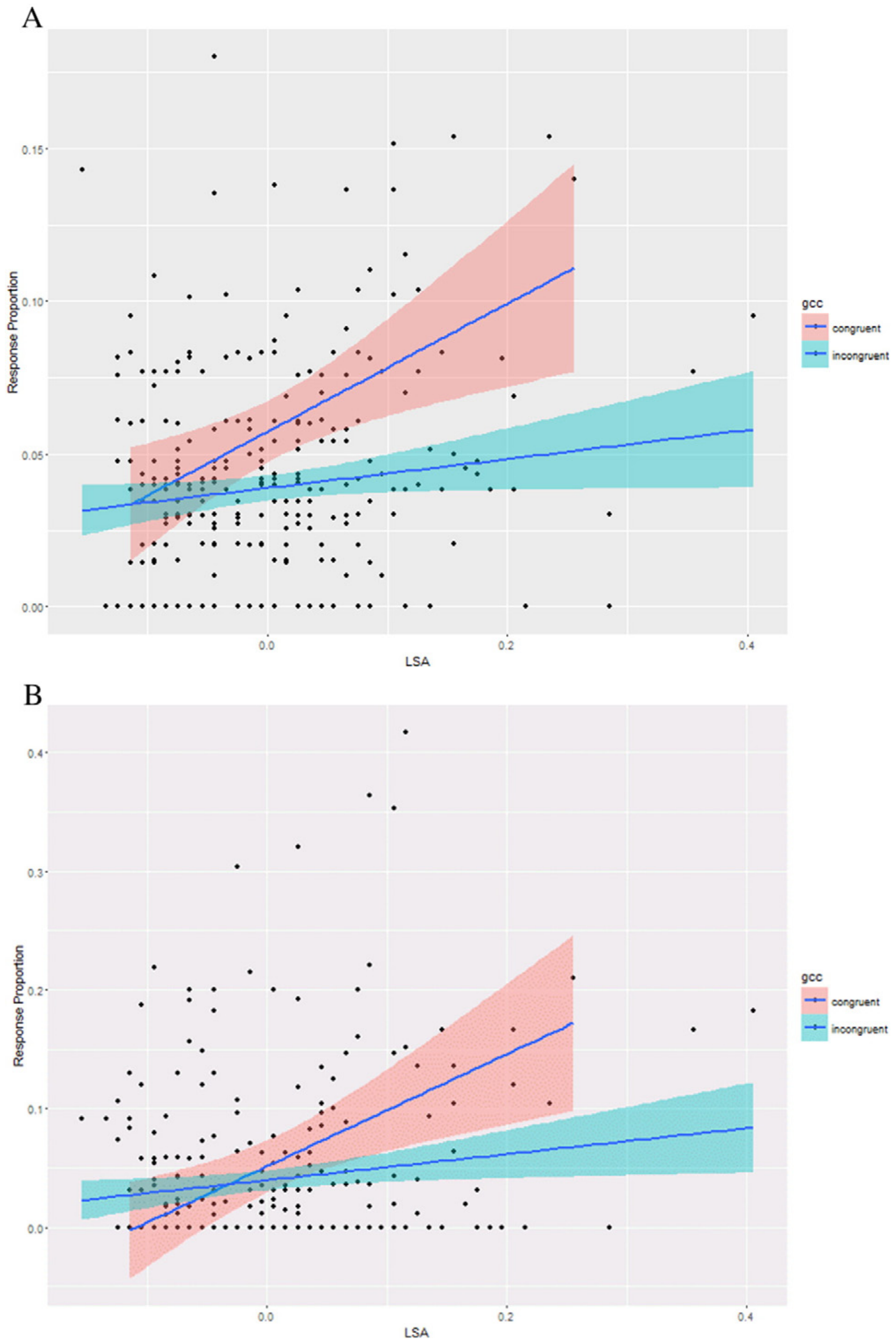

Fig. 1. A: synaesthetes' proportion of responses as a function of grapheme-colour congruency and LSA score (note: y-axis denotes logit transformed proportions). B: controls' proportion of responses as a function of grapheme-colour congruency and LSA score (note: y-axis denotes logit transformed proportions).

synaesthetes and non-synaesthetes were also observed for concept-colour pairings.

3.1. Participants

Twenty-five non-synaesthetes were recruited via online advertisements and word-of-mouth. Their mean age was 21.37 years (SD = 2.87), and 18 were female and 7 were male. Two reported being left-handed, and the rest right-handed. All participants provided written informed consent prior to participation.

We took steps to ensure that the participants in this experiment were not synaesthetes but non-synaesthete controls. Of the 25 total participants, 22 completed the online battery for this purpose (Eagleman et al., 2007), while another three were tested while the website for the battery was non-functional for several days and so these participants instead completed a paper-and-pencil measure that asked equivalent screening questions. Altogether, the battery only identified one participant as a synaesthete (taste-colour, temperature-colour, and vision-taste), and so this participant was removed from the analysis. Two others were identified as having absolute/perfect pitch (which is often associated with synaesthesia but not actually a form of synaesthesia itself), and so they were retained for analysis.

3.2. Apparatus and materials

These were identical to Experiment 1A.

3.3. Procedure

Participants were tested individually. They completed the synaesthesia battery on a laptop computer, and then completed a custom paper inventory that listed the 24 conceptual cue items on the left with space on the right for them to describe in writing the colours that they associate or imagine in response to the items. They were asked to leave items blank if they did have any colour to report for that particular cue. Below, Table 5 shows the frequency of report of each colour for each of the conceptual cues. Table 6 shows the most frequently reported colour for each item.

Table 6
Non-synaesthetes' most frequently-reported colour in response to each of the concept words.

Concept word	Most frequently associated colour
Bliss	Pink/blue
Cheerful	Yellow
Happy	Yellow
Joy	Yellow
Victory	Red
Positive	Green
Aircraft	White
Genius	Green
Peak	White
Sun	Yellow
Star	White
Tower	Grey
Unhappy	Blue
Sorrow	Black/blue
Negative	Black
Miserable	Grey
Doom	Black
Bleak	Grey
Underground	Brown/black
Underworld	Black
Grave	Grey
Mud	Brown
Trash	Green
Puddle	Brown

3.4. Results & discussion

To examine whether language-use predicted the frequency with which controls selected particular colours as associated with given concept words, we firstly selected for analysis the colour dimensions which had 10 or more responses associated with them as per Experiment 1A. Our statistical analyses strategy was also the same as in Experiment 1A: the factorial combination of LSA and grapheme-colour correspondence were entered into the model, and age of acquisition, imageability, and log frequency were entered as main effects. The most maximal model that converged had random intercepts for concept and colour, by-concept and by-colour random slopes for grapheme-colour correspondence and by-concept

Table 5
The frequency of report of each colour for each of the conceptual cues made by the non-synaesthetes. The same categorisation procedure was followed as for Experiment 1A and the full list of categorisation decisions can be found in Appendix 3. Also as per Experiment 1A, these absolute frequencies were converted to proportions of responses per colour for analysis.

	Cream	Yellow	Green	White	Brown	Orange	Black	Pale blue	Purple	Blue	Grey	Silver	Dark grey	Red	Dark blue	Gold	Dark red	Pink
Bliss	2	4	3	2		3		3	1	5				2			1	5
Cheerful		18	1			3								3				2
Happy		13	4	1		1				1				2		1	1	2
Joy	2	9		2		4		1		1		1		4				2
Victory		3	1			3						1		9	2	3	1	1
Positive		5	6	3		2				3				5				
Aircraft	1			17						4	6							
Genius		1	5			1	2		2	3	1			2				
Peak		1	1	6	4		3		2	4	3							
Sun		19		3		8								1				
Star		9		12			2			2	1	4				1		
Tower				2	4		3				13	2		2			1	
Unhappy							6			10	6		1		4			
Sorrow		1	1		1		7	1	1	7	5		1		1		1	
Negative				1			11		2	1	3			5	1		1	
Miserable							5		2	5	9		2		2			
Doom				1			11				6		1	3			2	
Bleak	1		1	2			4				10							
Underground		1			10		10				3		1					
Underworld		2		1	5		11			1	4			7	1		2	
Grave			1	1	6		4				13			1				
Mud					24									1				
Trash			7	1	4		5			1	7							
Puddle			1	1	10		1	2		4	6							

Table 7
Liner mixed effects models predicting non-synaesthetes' concept-colour frequency reports. $^*p < 0.05$. For model formula, see Appendix 6.

	β	SE(β)	t
Intercept	0.08	0.01	8.6*
LSA	0.28	0.11	2.46*
Grapheme-colour-congruency	0.03	0.03	0.944
Log frequency	0.017	0.02	0.946
Age of acquisition	0.001	0.00	0.25
Imageability	−0.01	0.01	−1.37
LSA ∗ Grapheme-colour congruency	0.70	0.32	2.22*

random slopes for LSA, age of acquisition, and imageability. The results are reported in Table 7.

Table 7 shows that, like the synaesthetes in Experiment 1A, LSA significantly predicted the control participants' concept-colour matching, such that more highly associated concept-colour pairings were more likely to be reported. Unlike in Experiment 1A, grapheme-colour congruency and age of acquisition did not predict colour-concept matching. However, as in Experiment 1A, there was a significant LSA by grapheme-colour congruency interaction. Fig. 1B plots the interaction, showing that as the strength of the association between concept and colour (as measured by LSA) becomes stronger, the effect of grapheme-colour consistency becomes stronger.

Finally, we investigated whether there were any substantial statistical differences between the two groups (synaesthetes versus controls) by comparing them in one overall analysis. We used the same analysis strategy as before, but added group as a between-participants variable. Specifically, the factorial combination group, LSA, and grapheme-colour congruency were entered into the model, as were main effects of age of acquisition, imageability, and log word frequency. Despite the fact that there were minor differences across the two groups, there were no significant interactions with group. There were only two significant model terms: (i) a significant positive effect of LSA on concept colour matchings ($\beta = 0.35$, $SE(\beta) = 0.102$, $t = 3.43$, $p < 0.05$), and (ii) a significant LSA by grapheme-colour congruency interaction ($\beta = 0.80$, $SE(\beta) = 0.22$, $t = 3.52$, $p < 0.05$). The full model output is shown in Appendix 7. This suggests that the concept-colour pairings were similar for synaesthetes and controls, such that both language use patterns relating the concepts to colours as well as the typical colour associated with starting letter of each concept word predict these associations for both groups. Moreover, the predictive value of each variable (LSA versus grapheme-colour congruency) increases as score on the other variable increases for both groups. This indicates that they are interrelated.

4. General discussion

The present study demonstrated that both language association statistics and the prototypical colour associated with the first letter of the word reliably predicted synaesthetes' and controls' concept-colour associations, and also interacted such that as values on LSA increased, so did the impact of grapheme-colour congruency. The fact that LSA was predictive in its own right is consistent with the broad conclusions from previous research implicating a psycholinguistic basis to synaesthesia (Simner, 2007), but it is also novel in that it is the first to demonstrate that language association statistics play a key role in explaining the observed associations. That is, rather than the observation that high-frequency graphemes tend to be paired with high-frequency colours (Simner et al., 2005), here we showed that the systematic *relationship* between concept words and colours influenced the manifestation of specific inducer-concurrent pairings in synaesthesia. This means that, for example, the fact that synaesthetes are most likely to associate *happy* with *yellow* is predicted by the fact that *happy* and *yellow* co-occur together in language more often than would be expected by chance. Similarly, synaesthetes are more likely to associate *sorrow* with *blue*, for which there is also linguistic evidence in the ambient language. Furthermore, the fact that the same pattern of associations was observed for the non-synaesthetes controls suggests that the associations for both groups may emerge from a shared linguistic experience. The difference is that this results in a perceptual experience for synaesthetes, whereas it is more of a cognitive association for non-synaesthetes. Of course, here we have simply measured language associations, and therefore can only speculate about what causal role exposure to regularities in language may play in the development of these associations: it could equally be the case that another factor is responsible for creating both the concept-colour pairings and the language associations. But if language is not shaping our basic cognition and perception, then at the very least, it is an intricate and insightful reflection of these processes.

The other interesting result here was that the colour that is typically associated with the first letter of each of the concept words also predicted the colour that participants were likely to report for the word, and this was particularly true when LSA scores for a given concept-colour pairing were high. This means, for example, that participants were most likely to associate the word *genius* with the colour green was predicted by the fact that green is one of the two prototypical colours for the letter *g*, but only to the extent that '*genius*' and '*green*' tended to be associated in language according to LSA. The fact that first grapheme colour was important in explaining concept-colour pairings is consistent with previous research indicating that the first letter of a word plays a role in shaping the synaesthetic colour experience for the whole word. For example, in one report, coloured hearing (speech perception) for nine synaesthetes tended to be based on graphemes rather than lexemes (Baron-Cohen, Harrison, Goldstein, & Wyke, 1993), and for another seven synaesthetes who experience colour in response to linguistic stimuli, there were systematic relationships between the colours generated by words and those generated by the graphemes (Ward, Simner, & Auyeung, 2005). Furthermore, in one individual, linguistic subcomponents of words, such as word stress and letter position influenced the colours experienced (Simner et al., 2006a). In the present study, it was particularly interesting that a) this influence of the first letter was present for both the synaesthetes and the non-synaesthete groups, suggesting that it arises from an influence common to both groups, b) the effect of grapheme-colour congruency depended on LSA score for the association between the word and the colour. The current correlational data do not allow us to say with any certainty what the nature of the relationship is between grapheme-colour pairings and word-colour pairings. However, the commonality between the groups and the interaction between the two variables does hint at the possibility that the prototypical colours for the letters might shape the colours for the words. Children likely learn the letter '*g*' well before they acquire a word like *genius*, and therefore it makes most sense for the letter *g* to influence *genius* to green, and this association is then reflected in language patterns. But then where do the prototypical colours for letters come from? Some previous research has suggested that exposure to particular patterns early in life (e.g. the colour that letters are shown in alphabet posters or magnets) may have an enduring effect on synaesthetic associations (Witthoft, Winawer, & Eagleman, 2015). Another possibility is that commonly-used words influence the colours for particular graphemes. For example, *a* could be red because apples are a prototypical object beginning with the letter *a*, and are typically red. Furthermore, *b* is blue and brown, *g* is green, *p* is pink, and *y* is yellow, suggesting that colour words themselves might influence the colouring of these particular letters. However, this is clearly only at best a partial explanation, because *g* can also be brown, *p* blue, *y* green, and many other letters have colours that do not appear to be related to a colour label (e.g., *e* is green and yellow, *z* is black). Regardless of the precise mechanism, the present results show that both synaesthetes and controls do not randomly pair letters with colours, but are instead sensitive to these shared systematicies.

Independent of the influence of individual graphemes, words also make an independent contribution to synaesthetic colours over and above the contribution of the component letters. In a prior study investigating synaesthetic colours in response to compound words (e.g., rainbow = rain + bow) in 19 synaesthetes, it was found that whether a single, unitary colour was experienced for the word, versus two colours, one for each of the subparts of the compound word, depended on the frequency of the compound word. That is, frequently-used compound words, elicited a single synaesthetic colours (Mankin, Thompson, Branigan, & Simner, 2016). This is evidence that it is not invariably the case that lexical-colour synaesthesia can be explained via a conglomeration or competition of component pairings. Similarly, weekday colour synaesthesia has been observed without any underlying grapheme-colour synaesthesia (Simner et al., 2006b). Our results are consistent with this notion that words can influence colour in their own right. If it were only the first letter that were responsible for creating the colour associations, then LSA scores between the concept word and the associated colour would not have been a reliable predictor of concept-colour pairings. Importantly, LSA was predictive not only for synaesthetes, but also for controls in the absence of synaesthesia.

The fact that LSA scores were predictive of concept-colour pairings provides convergent evidence for the broader notion that language appears to play a powerful role in shaping our attentional and perceptual mechanisms. Also consistent with this notion is the finding that the spatial mapping of concepts in unselected samples is predicted by language use statistics (Goodhew et al., 2014; Hutchinson & Louwerse, 2013; Louwerse, 2008; Louwerse & Jeuniaux, 2010). This is noteworthy, given that earlier explanations for such conceptual cueing effects centred on notions such as *perceptual simulation* (Dudschig, De la Vega, & Kaup, 2015; Meier & Robinson, 2004; Zwaan & Yaxley, 2003) derived from the *embodied cognition* framework (Barsalou, 1999, 2008; Gallese & Lakoff, 2005). That is, according to this idea, words shift attention due to our perceptual experience of objects in particular locations. For example, sun shifts attention upwards in space because of our perceptual experience of the sun being above us. Such models, however, while offering plausible explanations for the mapping of concrete words (e.g., *sun*, *sky*, *grass*), suffer from some difficulty in explaining the spatial mapping of abstract concepts for which we do not have direct perceptual experience (e.g., *dream*, *bliss*, *devil*) (but see Dudschig et al., 2015). Applying the same logic to the present study, the embodied cognition framework predicts that participants might associate *aircraft* with ‘white’ because of perceptual experience of white aircraft in the world around us. However, a model of perceptual simulation struggles to explain how abstract words, such as *bliss*, for which we have no direct perceptual experience of a single tangible object, also come to be associated with ‘blue’. The present study, therefore, further bolsters support for the importance of language in explaining systematic cognitive associations.

One could consider this creating a conundrum: how is it that language plays such an important role in a group who perhaps by definition, perceptually simulate? There is a clear way to resolve this: while language association and perceptual simulation are distinct theoretical mechanisms, they are not necessarily mutually exclusive (see Louwerse & Jeuniaux, 2010 for evidence of independent contributions of embodiment and language processing to the spatial mapping of concepts). It is highly likely that the two interact, such as systematic patterns in language being shaped by our perceptual experience of objects and their colours in the world around us, and the reverse could also occur: learning the prototypical colour of an object via language, even without direct perceptual experience. It could be speculated that synaesthetes might even perceptually simulate the experience of learning a particular word (e.g., seeing ‘*Tuesday*’ as red because it was red on a poster when learning these words). However, even if they are conceptualised as entirely independent mechanisms, then it still leaves open the possibility that both language association and perceptual simulation contribute to concept-colour associations. Here we have not refuted perceptual simulation, instead, we have shown convincing evidence for language association.

While it plausible that some of the concept-colour associations observed here may also be influenced by perceptual simulation (e.g., *grave*-grey), perceptual simulation cannot explain the associations between more abstract concepts and colours (e.g., *doom*-black, *cheerful*-yellow), since we would have no direct perceptual experiences to shape these associations. The present evidence instead suggests that such associations may be acquired and transmitted by systematic tendencies embedded in language. This is also consistent with other evidence that suggests a psycholinguistic basis to synaesthetic experience in other domains such as lexical-gustatory synaesthesia (Simner, 2007; Simner & Haywood, 2009; Ward & Simner, 2003).

It should be acknowledged that in the present study we had to rely on synaesthetes' self-reports of synaesthetic colours experienced for the selected concept words. This is because while the validated battery (Eagleman et al., 2007) contains tests for consistency and behavioural speeded-response congruency effects for grapheme-colour synaesthesia among others, it does not have a more general lexical-colour category. This is understandable: it would not be feasible to test synaesthetes' associations for all possible words. It would be useful, however, if the battery could be extended to incorporate, for example, a test for colours for some of the more common (non-weekday) words for which synaesthetes experience colours. For the present study, however, this means that we had a two-stage process for inferring the presence of lexical-colour synaesthesia: (1) that the synaesthete successfully passed the battery grapheme-colour, and then (2) we relied on their self-reports of colours elicited by our concept words. We asked participants to leave items blank on our paper-and-pencil measure if they did not have any colours for those words, and synaesthetes did indeed leave items blank, demonstrating that they were willing to comply with this instruction. From this we infer that synaesthetes were providing us with genuine reports of their experienced colour. However, it must be acknowledged that not having behavioural indicators of reliability or congruency to verify this is a limitation of the present study.

Furthermore, we restricted the analysis to colours that had >10 responses associated with them. It remains to be seen how predictive language is for more uncommonly reported colours. Moreover, it should also be acknowledged that while we were able to isolate two significant predictors of concept-colour pairings in the current study, this by no means indicates that we have captured all of the factors that may influence concept-colour pairings. For instance, for the concrete words, it could be that the colour of a prototypical instance of that object influences the colour for the word. More specifically, *mud* might be associated brown because mud is prototypically brown. We did not have such a variable in our analysis. However, even if such a variable was a significant predictor, it would be difficult to accurately ascertain where such prototypically arises from – is it perceptual experience, or language? The soil in large parts of Australia is in fact red, producing mud that is more red than brown. However, even if one's experience is exclusively or predominately of red mud, one could still come to appreciate that mud is prototypically brown, but this may be via language (e.g. story books about brown mud) rather than perceptual experience. While these words are not on our list per se, there are a number of other examples that illustrate how prototypicality can clash with perceptual experience. Fire engines are prototypically red, whereas in Canberra (Australia's capital city) they are lime green for improved visibility in low-light conditions. Christmas prototypically calls to mind snow, despite the fact that Christmas in the southern hemisphere occurs during the height of summer, and many children in warmer parts of Australia grow up never having seen actual snow. Altogether, the point we wish to make is that while it is a limitation of the study that we did not include a variable for prototypical colour, we also wish to highlight the uncertainty in understanding the origin of such prototypicality, and the difficulty in even having a variable that accurately captures all of the diversity of individuals' unique perceptual experiences.

It may also be the case for the abstract words that their emotional valence influences the selected colour, with more positive words producing lighter colours (such as yellow), and more negative words producing darker colours (such as blue and black). Indeed, research in other domains has shown that people automatically associate positive valence with brighter colours (Meier, Robinson, & Clore, 2004). Our results do not preclude such a possibility, and such systematicity may even actually be encapsulated within the LSA variable. That is, language may be the specific means for instantiating such relationships, which belong to a broader category of valence and brightness. Future research can examine such possibilities.

In conclusion, the present study provides evidence that both language association statistics and prototypical colour for the first letter of each word reliably predicted the associations between concepts and colours reported by both synaesthetes and non-synaesthete controls. This suggests that language can determine fundamental perceptual processes such as the experience of synaesthetic colour, and can also influence broader associations for those who do not experience synaesthetic colours.

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Appendix 1

Synaesthete #	Types of synaesthesia	Consistency scores (only for letter-colour)[b]	P/A Score	Meet criteria for inclusion in analysis?
1	Numbers → Colour		−2.2	N
	Months → Colour			
2	Numbers → Colour		−2.7	N
	Months → Colour			
	Smell → Colour			
	Personalities → Colour			
	Emotion → Colour			
3	Numbers → Colour		−2.7	Y
	Letters → Colour	**0.68**		
	Weekdays → Colour			
	Months → Colour			
	Musical chords → Colour			
	Musical instruments → Colour			
	Taste → Colour			
	Smell → Colour			
	Temperature → Colour			
	Orgasm → Colour			
	Emotion → Colour			
	Mathematical theorems → Colours, shapes, sensation			
4	Numbers → Colour		−2.7	Y
	Letters → Colour	**0.73**		
	Weekdays → Colour			
	Months → Colour			
5	Numbers → Colour		−2.0	Y
	Letters → Colour	**0.57**		
	Greek alphabet → Colour			
6	Musical pitch → Colour		0	N
	Musical chords → Colour			
	Musical instruments → Colour			
	Taste → Colour			
	Smell → Colour			
	Pain → Colour			
7	**Letters → Colour**	**0.81**	−2.3	Y
	Musical chords → Colour			
8	Numbers → Colour		−2.2	Y
	Letters → Colour	**0.56**		
	Weekdays → Colour			
	Months → Colour			
	Chinese numbers → Colour			
9	**Letters → Colour**	**0.85**	−2	Y
10	Numbers → Colour		−1.3	Y
	Letters → Colour	**0.51**		
	Weekdays → Colour			
	Months → Colour			
	Emotion → Colour			
11	Numbers → Colour		1.5	Y
	Letters → Colour	**1.16**		
	Weekdays → Colour			
	Months → Colour			
	Chinese numbers → Colour			
	Sequences → Spatial locations			
	Musical pitch → Colour			
	Musical chords → Colour			

(continued on next page)

Appendix 1 *(continued)*

Synaesthete #	Types of synaesthesia	Consistency scores (only for letter-colour)[b]	P/A Score	Meet criteria for inclusion in analysis?
	Musical instruments → Colour			
	Chinese characters → Colour			
	Taste → Colour			
	Pain → Colour			
	Touch → Colour			
12	Weekdays → Colour		−2	N
	Musical pitch → Colour			
	Musical chords → Colour			
	Musical instruments → Colour			
	Taste → Colour			
	Smell → Colour			
	Personalities → Colour			
	Temperature → Colour			
	Vision → Sound			
	Sound → Smell			
13	Numbers → Colour		−0.7	Y
	Letters → Colour	**0.73**		
	Weekdays → Colour			
14	Numbers → Colour		−0.5	Y
	Letters → Colour	**0.82**		
	Weekdays → Colour			
	Months → Colour			
	Smell → Colour			
15	Sequences → Spatial locations		−1	N
	Vision → Smell			
	Sound → Taste			
	Seeing → Touch (feel sensation from seeing people getting touch)			
16	Personalities → Colour		−0.8	N
17	Numbers → Colour		−0.8	Y
	Letters → Colour	**0.78**		
	Weekdays → Colour			
	Months → Colour			
	Sequences → Spatial locations			
	Musical instruments → Colour			
	Pain → Colour			
	Personalities → Colour			
	Orgasm → Colour			
	Sounds → Touch			
18	Absolute pitch/perfect pitch[a]		−0.7	Y
	Numbers → Colour			
	Letters → Colour	**0.78**		
	Weekdays → Colour			
	Months → Colour			
	Musical pitch → Colour			
19	Numbers → Colour		−2.7	Y
	Letters → Colour	**0.32**		
	Weekdays → Colour			
	Months → Colour			
	Sound → Shapes and colour			
20	Numbers → Colour		−3.2	N
	Weekdays → Colour			
21	Pain → Colour		0	N
	Taste → Touch (foods “taste” a certain “shape” rather than flavour)			
22	Numbers → Colour		−3	Y
	Letters → Colour	**0.32**		
	Weekdays → Colour			
	Months → Colour			
23	Weekdays → Colour		0	N
	Months → Colour			
	Sequences → Spatial locations			
24	Numbers → Colour		−1.2	Y
	Letters → Colour	**0.76**		
	Sequences → Spatial locations			
	Pain → Colour			
25	Numbers → Colour		−0.7	Y
	Letters → Colour	**0.31**		
	Weekdays → Colour			
	Months → Colour			
	Sequences → Spatial locations			
	Personalities → Colour			
	Temperature → Colour			
	Emotion → Colour			
26	Numbers → Colour		−2	Y

Appendix 1 *(continued)*

Synaesthete #	Types of synaesthesia	Consistency scores (only for letter-colour)[b]	P/A Score	Meet criteria for inclusion in analysis?
	Letters → Colour	**0.86**		
	Weekdays → Colour			
	Months → Colour			
27	Numbers → Colour	0.51	−1.7	N
	Weekdays → Colour	0.4		
	Months → Colour	0.91		
	Musical instruments → Colour			
	Smell → Colour			
	Sound → Taste			
28	**Letters → Colour**	**0.49**	0	Y
	Weekdays → Colour			
29	Sequences → Spatial locations		−0.2	N
30	Absolute pitch/perfect pitch[a]		−1.3	Y
	Numbers → Colour			
	Letters → Colour	**0.85**		
	Weekdays → Colour			
	Months → Colour			

Inducer-concurrent pairs in bold signify the forms of synaesthesia recorded in the battery used to identify lexical-colour synaesthetes.

P/A score = Projector/Associator score. This score is a quantification of the extent to which a given synaesthete has their experience internally ("in their mind's eye") – characteristic of *associator* synaesthetes, as opposed to externally in space – characteristic of *projector* synaesthetes (Dixon, Smilek, & Merikle, 2004). P/A scores <0 are indicative of associator status, whereas scores >0 are indicative of projector status (Eagleman et al., 2007).

[a] While *Absolute pitch/perfect pitch* is not actually a form of synaesthesia, since the battery records it we report it here for interest.

[b] Consistency scores <1 are indicative of synaesthesia. Note that where a participant has colours for both letters and digits, the battery reports a single combined consistency value for these, and this is what is reported next to letter → colour form of synaesthesia.

Appendix 2

Categorisation decisions made about to which broader colour category synaesthetes' reports should belong.

- Moss green → green
- Sky blue → pale blue
- Light blue → pale blue
- Dark washed out pink → pink
- Navy → dark blue
- Olive green → green
- Lime green → green
- Dark green → green
- Dark purple → purple
- Maroon → dark red
- Dark brown → brown
- Beige → cream
- Faded blue → pale blue
- Light grey → grey
- Mustard → yellow, orange, and brown
- Muted red → red
- Light brown → brown
- Dark → black
- Steel blue → blue, grey
- Polished steel → grey
- Cherry → dark red
- Light pink → pink
- Dark pink → pink
- Charcoal → dark grey
- Salmon → pink
- Forest green → green
- Mottled green → green
- Light purple → purple
- Light yellow → yellow
- Army green → green

Not classified:

One synaesthete reported both *sun* and *mud* as the colour "mud". It was unclear what colour this should be treated as. At first blush it might be considered brown, but since this is one of the items in the list, it seemed presumptuous to give it a colour on behalf of the participant. It was therefore not classified.

Appendix 3

Categorisation decisions made about to which broader colour category non-synaesthetes (controls) reports should belong.

- Light green → green
- Light blue → pale blue
- Navy blue → dark blue
- Light brown → brown
- Indigo → blue + purple
- Maroon → dark red
- Dark brown → brown
- Lemon yellow → yellow
- Hazy blue → blue
- Bright yellow → yellow
- Light grey → grey
- Fluorescent green → green
- Light orange → orange
- Faint green → green
- Off-white → cream
- Clay → red + brown
- Dull green → green
- Transparent grey → grey
- Dark green → green
- Sparking yellow → yellow
- Dark yellow → yellow
- Light yellow → yellow
- Light cream → cream
- Earth brown → brown
- Sodium lights → yellow
- Light brown → brown
- Brownish → brown
- Beige → cream
- Fluorescent yellow → yellow
- Army green → green
- Sky blue → pale blue
- Soil brown → brown

- Algae green → green
- A dirty blue → blue
- Metallic → grey
- Light pink → pink
- Dark green → green
- Burgundy → dark red

Not classified:

Two participants reported *trash* as ‘multicoloured’. Since this was not a colour-selective response, it was not scored. Similarly, one participant responded ‘reflection of dary [sic] images’ and another simply ‘clear’ in response to *puddle*. Again, these did not fit any of the above categories and were thus not scored. Furthermore, one participant responded that was *miserable* was ‘the transparent tear colour’, and one reported that *doom* was a ‘dull colour’ none of which clearly fitted the above categories and so were not scored.

Appendix 4

This shows the overall frequency in language use for each of the concept words in the Google Ngram corpus, which are expressed as frequencies given the total number of words (currently >360 billion words, Michel et al., 2011)

Word	Frequency (%)	Log transformed frequency
Bliss	0.0005602744	−3.25
Cheerful	0.0005958327	−3.22
Happy	0.0064319210	−2.19
Joy	0.0033487511	−2.48
Victory	0.0029709706	−2.53
Positive	0.0108060508	−1.97
Aircraft	0.0025558331	−2.59
Genius	0.0014736543	−2.83
Peak	0.0029772683	−2.53
Sun	0.0086363108	−2.06
Star	0.0045142252	−2.35
Tower	0.0021202159	−2.67
Unhappy	0.0010516836	−2.98
Sorrow	0.0010806500	−2.97
Negative	0.0088178458	−2.05
Miserable	0.0008943195	−3.05
Doom	0.0003548769	−3.45
Bleak	0.0003332908	−3.48
Underground	0.0013496220	−2.87
Underworld	0.0002743384	−3.56
Grave	0.0022146117	−2.65
Mud	0.0013400655	−2.87
Trash	0.0005697144	−3.24
Puddle	0.0001217760	−3.91

Appendix 5

	Log frequency	AoA	Imageability
LSA	−0.123	−0.135	−0.123
Imageability	0.102	−0.422*	
AoA	−0.287		

* $p < 0.05$ (2-tailed).

Appendix 6

Model used in Experiment 1A. model = lmer(response ~ (LSA + gcc)^2 + log_freq + imageability + AoA + (1|concept) + (1|colour), data = data).

Model used in Experiment 1B. model = lmer(response ~ (LSA + gcc)^2 + log_freq + imageability + AoA + (1|concept) + (1|colour) + (1 + gcc|concept) + (1 + gcc|colour) + (1 + LSA + AoA + image|concept), data = data)

Overall model comparing groups: model = lmer(resp ~ (group + LSA + gcc)^3 + log_freq + imageability + AoA + (1|concept) + (1|colour) + (1 + group|concept) + (1 + LSA|concept), data = data)

Appendix 7

Full model output for overall analysis.

	β	SE(β)	*t*
Intercept	0.08	0.01	9.11*
Group	−0.002	0.01	−0.22
LSA	0.35	0.1	3.43*
GCC	0.02	0.02	1.36

Appendix 5 *(continued)*

	β	SE(β)	*t*
Log freq	0.01	0.01	0.70
Imageability	−0.004	0.005	−0.80
AoA	0.004	0.003	1.30
Group X LSA	−0.18	0.11	−1.70
Group X GCC	0.012	0.03	0.49
LSA X GCC	0.80	0.23	3.52*
Group X LSA X GCC	−0.43	0.32	−1.36

* $p < .05$

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