BRIEF REPORT

Second-order mappings in grapheme–color synesthesia

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Abstract Typically, the search for order in grapheme–color synesthesia has been conducted by looking at the frequency of certain letter–color associations. Here, we report stronger associations when second-order similarity mappings are examined—specifically, mappings between the synesthetic colors of letters and letter shape, frequency, and position in the alphabet. The analyses demonstrate that these relations are independent of one other. More strikingly, our analyses show that each of the letter–color mappings is restricted to one dimension of color, with letter shape and ordinality linked to hue, and letter frequency linked to luminance. These results imply that synesthetic associations are acquired as the alphabet is learned, with associations involving letter shape, ordinality, and frequency being made independently and idiosyncratically. Because these mappings of similarity structure between domains (letters and colors) are similar to those found in numerous other cognitive and perceptual domains, they imply that synesthetic associations operate on principles common to many aspects of human cognition.

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At least 1% of the population reliably associates particular colors with letters and numerals (Simner et al., 2006). Despite an explosion of research on *grapheme–color synesthesia* over the past two decades, little is known about how these associations are made. Why does Jane see the letter M as a deep purple, while John associates the same letter with forest green? Here we verify that there are several different sources of synesthetic associations, and we investigate both how they interact with each other and what aspects of synesthetic color they influence.

To date, synesthesia research has documented a number of regularities in the grapheme–color pairs of individuals. For example, English speakers often associate the letter B with blue or brown, G with green, and so on for the first letters of other common color names (Barnett et al., 2008; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005). Similarly, some synesthetes have adopted the colors of letter-shaped fridge magnets used in their childhoods (Witthoft & Winawer, 2006). These are regularities in *first-order relations*—that is, between nonrelational properties of a letter (such as its shape or name) and dimensions of synesthetic color such as hue and lightness (see also Day, 2005).

A parallel line of research has begun to investigate grapheme–color pairings by looking for *second-order relations*, or "relations between relations." For example, letters with similar shapes, such as E and F, tend to be associated with synesthetic colors that are similar in hue (Brang, Rouw, Ramachandran, & Coulson, 2011; Eagleman, 2010; Jürgens, Mausfeld, & Nikolic, 2010; Watson, Akins, & Enns, 2010).

Here there is a correlation between two relations: A relation of similarity in the domain of letter shape is correlated with a relation of similarity in the domain of synesthetic color. Importantly, second-order relations can exist independently of first-order pairings. That is, two synesthetes may each assign different colors to E, but so long as each individual's color for F is similar to that individual's color for E, this constitutes a second-order relation between letter shape and synesthetic color. Thus, second-order letter–color associations may not be apparent when looking at first-order relations.

A variety of second-order influences on synesthetic color have been demonstrated. Marks (1975) noted that music–color synesthetes often associate higher pitches with brighter colors. In grapheme–color synesthesia, numerals and letters that appear more frequently in print tend to be associated with brighter (Beeli, Esslen, & Jäncke, 2007; Cohen Kadosh, Henik, & Walsh, 2007; Simner & Ward, 2008; Smilek, Carriere, Dixon, & Merikle, 2007) and more saturated (Beeli et al., 2007) colors. More frequent letters also tend to be associated with colors whose names are more common in spoken language (Rich et al., 2005; Simner et al., 2005). Each of these results has been reported as a first-order relation (correlations between *absolute values* on two dimensions), but they all imply second-order relations (correlations between *differences in values* on two dimensions). For example, the fact that more-frequent letters have brighter colors implies that letters that differ greatly in terms of frequency will *also* differ in terms of their brightness.

Two recent results have come directly from second-order analyses. First, as noted above, letters with similar shapes appear to be associated with similar synesthetic colors (Brang et al., 2011; Eagleman, 2010; Jürgens et al., 2010; Watson et al., 2010). Second, letters early in the alphabet tend to have colors that are quite distinct from each other, whereas later letters tend to have colors that are more similar to those of nearby letters (Eagleman, 2010). On Eagleman's view, this pattern stems from the order in which children learn their letters. The first letter learned is associated with an idiosyncratic color; the next letter is associated with a color that is easily distinguishable from the first; and each subsequently learned letter is associated with a color as distinct as possible from those already assigned. With each letter learned, however, the range of distinct color choices is diminished, and inevitably, letters learned later are associated with colors similar to some of those associated with earlier letters. Note that this interpretation implies a relation between letter ordinality and synesthetic color that is similar to Weber's fraction. In brief, a pair of letters that appear early in the alphabet (e.g., A and D) will be assigned colors that are more distinctive than will a pair of letters later in the alphabet (e.g., S and V), even though they are equal numbers of steps apart in

absolute units (three, in this example). Such a finding requires a second-order perspective: When one looks at absolute hue assignments, no relation with ordinality is found (Cohen Kadosh et al., 2007; Simner et al., 2005).

In line with these findings, we prefer to analyze second-order relations among grapheme–color pairs. Our primary motivation is that strong second-order mappings (with weaker first-order mappings) have often been observed in human perception more generally (e.g., we remember melodies, not absolute pitch, in music; facial configurations, not specific facial features, in vision; and words, not phonemes, in language). A secondary motivation is that second-order analyses allow for the easy investigation of the property of hue. Because luminance and saturation are one-dimensional properties of colors, they can be used in correlations or other linear analyses. Hue requires at least two dimensions, however, in order to be specified (e.g., blue-yellow or red-green), which makes it impossible to compute a simple correlation between hue and any other measure. *Differences* between hues, on the other hand, are one-dimensional, and thus amenable to linear analysis.

In the present study, we compared the colors assigned to letters by a large group of synesthetes ($N = 54$) with a wide variety of letter similarity measures taken from nonsynesthetic individuals. We sought to determine how different aspects of letter similarity (e.g., shape, order, and frequency) are related to synesthetic colors, and how these effects relate to each other. We were especially interested in how the various aspects of letter similarity might be related to two dimensions of color—namely, luminance and hue (the data set did not include saturation, and thus we could not verify the findings of Beeli et al., 2007). As noted above, differences in letter frequency have been shown to correspond to differences in luminance, while differences in hue have generally been overlooked, possibly because researchers have been looking for first-order relations. How letter shape and ordinality map separately onto luminance and hue remains an open question.

Data preparation

The RGB color values of each letter were provided by 54 confirmed grapheme–color synesthetes (data previously reported in Smilek et al., 2007). These values were recoded into CieLab color space, which more accurately describes human color discriminations and allows for the separation of color into luminance and hue components. There are 325 possible letter pairs (not including doubles of the same letter), and for each of these pairs we computed separate values for color distance (Euclidean distance in CieLab space), luminance distance (distance along

Table 1 Letter similarity measures used in the present study

Similarity Measure	Description
Shape difference	Euclidean distance in an 11-dimensional space defined using the basic letter shape features from Gibson (1969)
Frequency difference	Difference of two letters' frequencies divided by the sum of their frequencies (Lewand, 2000)
Ordinality difference	Difference of two letters' positions in the alphabet divided by the sum of their positions
Letter name similarity	Number of shared phonemes in two letter names (e.g., "bee" and "dee" have 1 shared phoneme, /i/)
Discrimination RT	Reaction time on a same–different discrimination task for uppercase letter pairs (Podgorny & Garner, 1979)
Ratings	
A (similarity)	Similarity ratings of uppercase letters (Boles & Clifford, 1989)
B (similarity)	Similarity ratings of lowercase letters (Boles & Clifford, 1989)
C (difference)	Difference ratings of uppercase letters (Podgorny & Garner, 1979)
Confusion	
A	Chance of confusing two briefly presented uppercase letters on a letter-naming task (Gilmore, Hersh, Caramazza, & Griffin, 1979)
B	Chance of confusing two uppercase letters (in Keepsake font) presented at low intensity on a letter-naming task (Gupta, Geyer, & Maalouf, 1983)
C	Chance of confusing two uppercase letters (dot-matrix font) presented at low intensity on a letter-naming task (Gupta et al., 1983)

the CieLab L-axis), and hue distance (distance in the CieLab ab plane). These values were averages of the distances across all 54 synesthetes.

A total of 11 measures of letter similarity were derived for comparisons with the synesthetic color data (see Table 1). *Shape difference* is the Euclidean distance in a letter-shape similarity space generated from 11 basic letter-shape features (Gibson 1969), such as the presence or absence of a diagonal line. *Frequency difference* and *ordinality difference* are the differences between the frequencies (Lewand, 2000) and positions in the alphabet of two letters, divided by their sum. *Letter name similarity* consists of the number of shared phonemes in the English names of two letters; for instance, the names of the letters B and D share one phoneme, /i/, and hence would have a letter name similarity of 1 (this is the phoneme co-occurence score used by Ward & Simner, 2003). These are examples of the familiar Weber fraction that describes perceived difference in numerous psychophysical domains. The remaining measures were previously published behavioral data on letter similarity, and thus may have been influenced by letter shape, frequency, order of acquisition, and (potentially) many other factors. These measures include *discrimination RTs*, from a same–different task in which the subjects were briefly presented with letter pairs (Podgorny & Garner, 1979); *comparison ratings* of letter similarity or difference (Boles & Clifford, 1989; Podgorny & Garner, 1979); and *confusion*, from letter-naming tasks using degraded stimuli (Gilmore, Hersh, Caramazza, & Griffin, 1979; Gupta, Geyer, & Maalouf, 1983).

Except where noted, all subsequent analyses were performed after binning the 325 letter pairs into 65 bins that each included five letter pairs. Bins were determined by the mean color distance of each letter pair across all 54 synesthetes, such that the first bin contained the five pairs whose two letters were, on average, most similar in color, and the last bin contained the five pairs whose two letters were, on average, most dissimilar in color.

Results

Letter similarity measures predict different aspects of color similarity

We computed the simple correlations of all of the letter similarity measures with color, luminance, and hue distance (see Table 2). Since multiple correlations were run, we corrected the p values, multiplying each by 7, as seven distinct types of measures were being compared with each of the color distance measures. We also used Spearman's rho for the correlations involving the three ratings, since they are ordinal measures.

Color distance and hue distance were both correlated with shape difference, ordinality difference, and Letter Confusion B. Luminance distance was correlated with frequency difference, and marginally correlated with Rating C and with Letter Confusion C. Thus, there appears to be a split between those

Table 2 Correlations between letter and color similarity

Similarity Measure	Color Distance	Luminance Distance	Hue Distance
Shape difference	.48***	.05	.50***
Frequency difference	.06	.34*	.01
Ordinality difference	.37*	.02	.39**
Ratings			
A (similarity)	−.08	−.28	−.05
B (similarity)	−.15	−.27	−.12
C (difference)	.13	.32	.09
Discrimination RT	−.21	−.26	−.19
Confusion			
A	.04	−.23	.07
B	−.39**	−.25	−.37*
C	−.27	.32	−.24
Letter name similarity	.02	.00	.02

Correlations with the ratings use Spearman's rho. All p values are Bonferroni corrected and > .1, except: $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$

aspects of letter similarity that predict synesthetic luminance and hue.

Letter shape and ordinality predict hue; letter frequency predicts luminance

All of the correlations described above can be accounted for in terms of only three mappings, shown in Fig. 1. A first mapping involves letter shape and synesthetic hue, a second involves letter ordinality and hue, and a third involves letter frequency and luminance. A regression model using only shape difference and ordinality difference to predict hue distance ($R^2 = .32$, $p < .001$) did not explain less variance

than one using all 11 letter similarity measures to predict hue distance ($p > .1$). However, removing either shape difference or ordinality difference from the reduced model resulted in significantly less explained variance ($p < .05$ in both cases). As Confusion B was also significantly correlated with hue distance (see Table 2), we tried adding it to this reduced model, but it did not explain any variance independently of shape and ordinality difference ($p > .2$). Similarly, a regression model using frequency difference as the sole predictor of luminance distance ($R^2 = .12$, $p < .01$) did not differ from a model using all 11 similarity measures as predictors ($p > .1$). We also tried a three-predictor model that included Rating C and Confusion C, as these were marginally correlated with luminance distance, but neither explained any variance independent of frequency difference.

Analyses of individual differences show that the mappings are independent

We computed the correlations for each of the mappings in Fig. 1 at the level of individual synesthetes. This revealed that these correlations were positive for a majority of the synesthetes [85%, 67%, and 54% for panels (a), (b), and (c), respectively, in Fig. 1]. Overall, 30% of the synesthetes had positive correlations for all three mappings, 48% had positive correlations for two of the mappings, and the remaining 22% had a positive correlation for only one mapping. Critically, there were no hints of correlations between any of these mappings, as tested by coding the presence or absence of each mapping as 0 or 1 for each synesthete, or by correlating the rank order of synesthetes on each mapping, as determined by the magnitude of their individual correlations (all ps > .2).
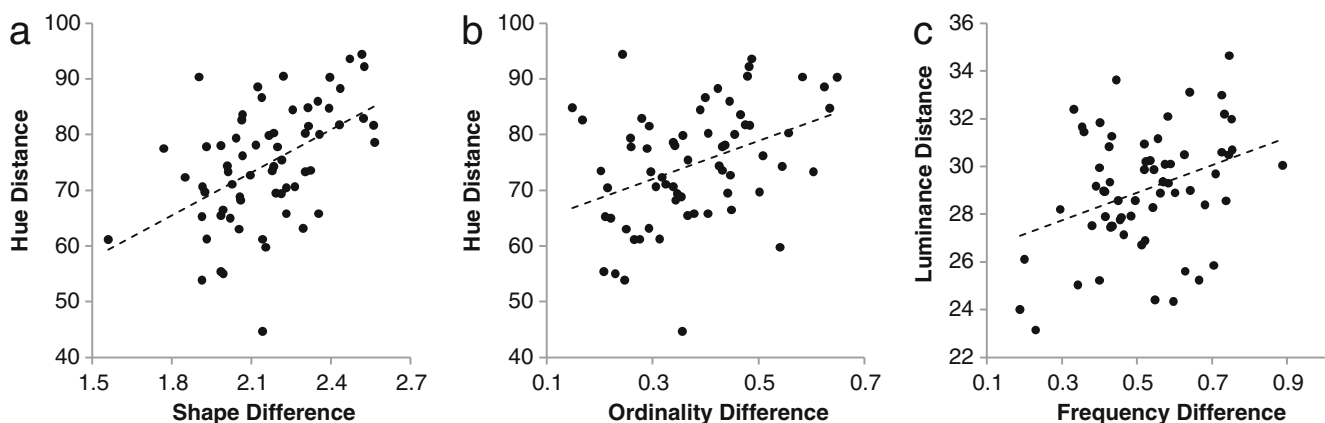

Fig. 1 Scatterplots of three second-order mappings between letter similarity and synesthetic color. The x-axes denote differences between letter pairs in (a) letter shape, (b) letter ordinality, and (c) letter frequency. The y-axes for panels (a) and (b) denote distance in terms of synesthetic hue; in panel (c), the y-axis denotes distance in terms of synesthetic luminance. The 65 data points in each plot were obtained by binning 325 letter pairs into five-pair bins and then averaging over 54 synesthetes (from Smilek et al., 2007)

Which aspects of shape matter?

The shape difference measure was further subdivided into 11 dimensions of shape that are important in letter identification (Gibson, 1969). Only two of these dimensions were significantly correlated with hue distance (after a Bonferroni correction)—namely, distance along the closed curve and repeated element dimensions (rs = .41 and .38, ps = .001 and .002, respectively; all other ps > .1). However, a model that used only these two dimensions to predict hue distance explained less variance than did a model using all 11 dimensions (p < .05). In the complete 11-predictor model, the only variables that made a significant independent contribution were distance along the closed curve, repeated element, and diagonal dimensions (all ps < .01). Thus, we tried a model using these three variables to predict hue distance (R^2 = .38, p < .001), and found that it did not predict less variance than the complete 11-predictor model (p > .18), but removing any one of these three dimensions from the model resulted in less explained variance (all ps < .05). Further study will be needed to determine why these features are especially important to synesthetes.

Discussion

These results confirm that three distinct aspects of letter similarity have a second-order influence on synesthetic color assignments. The shape, frequency, and ordinality of individual letters influence the colors assigned to them by synesthetes, and these three effects are completely independent of each other: For instance, an individual with a strong shape–hue association may or may not have a strong frequency–luminance association. Finally, each of these mappings is confined to a particular dimension of color space: Letter shape and ordinality are associated with hue, while frequency is associated with luminance.

Brang et al.'s (2011) cascaded cross-tuning model of synesthesia states that shape–color associations are the result of the coactivation of contiguous brain areas in the fusiform gyrus that represent letter form and color. This model does not currently account for the other relations we found, nor for the fact that each relation is confined to a particular dimension of color. Instead of looking for an explanation at the level of shared neurons, we offer two complementary hypotheses for these findings, both of which revitalize an old hypothesis of Calkins (1893): that synesthetic associations may arise for strategic reasons.

First, associating letter shapes and identities with hue might aid learning to read, but associating them with luminance might compromise reading performance. In vision, a common strategy is to process hue and luminance separately (cf. Gheorghiu & Kingdom, 2006, 2007; Kingdom, Beauce, & Hunter, 2004;

Kingdom & Kasrai, 2006; Liebe, Fischer, Logothetis, & Rainer, 2009; Nagai & Uchikawa, 2009; Shimono, Shiori, & Yaguchi, 2009), because each dimension provides different information about the environment (Hansen & Gegenfurtner, 2009). For example, a vital part of vision is to differentiate shadows from material objects. Since shadows are defined by differences in luminance, whereas objects usually differ from their background in both luminance and hue, it follows that hue edges are a more reliable cue to object boundaries than are luminance edges.

A similar moral applies in reading. Graphemes are usually presented as dark, achromatic elements on a lighter background, and thus are usually processed entirely on the basis of luminance contrast. Second-order relations between synesthetic hue and shape could provide an additional source of information to be exploited for such tasks as letter segmentation, identification, place-holding for visual saccades, search for letters, maintaining letter order in short-term memory, and so forth. However, similar mappings between synesthetic luminance and shape might interfere with the luminance-sensitive channels responsible for letter shape perception, and so could conflict with natural variations in luminance from the font and from illumination. Thus, synesthetes may exploit information about letter identity encoded in synesthetic hue, in addition to the systems that they share with nonsynesthetes, which use luminance contrast in the various cognitive operations involved in reading.

A complementary hypothesis for mapping hue and luminance to separate aspects of letter identity stems from differences in the ways that humans use hue and luminance to represent information. Take map reading as an example. Defining regions by hue typically allows for faster and more accurate judgments of categorical distinctions than does defining them by luminance, while luminance scales afford advantages for judgments about relative quantity or continuous magnitudes (Breslow, Trafton, McCurry, & Ratwani, 2010). This likely reflects the fact that variations in luminance have an underlying continuity, from dark to light, while hues are perceived categorically. As letter frequency varies along a continuum, then, it maps naturally to luminance. Letter shapes, on the other hand, are perceived categorically (Boles & Clifford, 1989), and thus map naturally to hue. Since letter ordinality also varies continuously, one might think that it should be associated with luminance. Recall, however, that we use letter ordinality as a rough index of the order of learning of individual letters, which are themselves seen as categorical objects (Eagleman, 2010), so the association between ordinality and hue is also consistent with this hypothesis.

Previous research has reported a number of first-order synesthetic color associations; for instance, the letters used to begin common color words are frequently associated with the colors named by these words, and the letters O and I are almost always black, white, or gray (Barnett et al., 2008; Day,

2005; Rich et al., 2005; Simner et al., 2005). We stress that the finding of second-order relations is complementary to such results. It appears that a wide range of factors, of both the first and second orders, can potentially influence letter–color mappings, as a good deal of variance in both luminance and hue still remains unexplained. Our analysis of individual differences suggests that these factors often coexist within individual synesthetes. That is, any given letter–color mapping might be influenced by a particular factor, but a different letter (or the same letter for a different synesthete) is quite likely to be colored according to a different factor.

In summary, examining relations involving differences between letters and their assigned colors has allowed us to directly compare and contrast multiple influences on synesthetic associations. The finding that second-order relations are pervasive in synesthesia is further evidence for the view that synesthesia builds on normal mechanisms (cf. Barnett et al., 2008; Simner et al., 2005). Though most of us may not reliably associate letters with colors, those of us who do tend to use principles common to other sensory and cognitive domains.

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