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Research report

Why is the synesthete's “A” red? Using a five-language dataset to disentangle the effects of shape, sound, semantics, and ordinality on inducer–concurrent relationships in grapheme-color synesthesia

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ABSTRACT

Grapheme-color synesthesia is a neurological phenomenon in which viewing a grapheme elicits an additional, automatic, and consistent sensation of color. Color-to-letter associations in synesthesia are interesting in their own right, but also offer an opportunity to examine relationships between visual, acoustic, and semantic aspects of language. Research using large populations of synesthetes has indeed found that grapheme-color pairings can be influenced by numerous properties of graphemes, but the contributions made by each of these explanatory factors are often confounded in a monolingual dataset (i.e., only English-speaking synesthetes). Here, we report the first demonstration of how a multilingual dataset can reveal potentially-universal influences on synesthetic associations, and disentangle previously-confounded hypotheses about the relationship between properties of synesthetic color and properties of the grapheme that induces it. Numerous studies have reported that for English-speaking synesthetes, “A” tends to be colored red more often than predicted by chance, and several explanatory factors have been proposed that could explain this association. Using a five-language dataset (native English, Dutch, Spanish, Japanese, and Korean speakers), we compare the predictions made by each explanatory factor, and show that only an ordinal explanation makes consistent predictions across all five languages, suggesting that the English “A” is red because the first grapheme of a synesthete's alphabet or syllabary tends to be associated with red. We

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propose that the relationship between the first grapheme and the color red is an association between an unusually-distinct ordinal position ("first") and an unusually-distinct color (red). We test the predictions made by this theory, and demonstrate that the first grapheme is unusually distinct (has a color that is distant in color space from the other letters' colors). Our results demonstrate the importance of considering cross-linguistic similarities and differences in synesthesia, and suggest that some influences on grapheme-color associations in synesthesia might be universal.

1. Introduction

Grapheme-color synesthesia is a neurological phenomenon in which a percept (the synesthetic *inducer*) elicits an additional, automatic, and consistent sensation (the synesthetic *concurrent*). In grapheme-color synesthetes – one of the most commonly-studied forms – a grapheme will elicit the perception of a color. Strikingly, the relationship between a specific inducer and concurrent is highly consistent within a single synesthete: when asked to choose (using a color-picker) the color elicited by a grapheme, grapheme-color synesthetes will consistently choose the same color, even when testing periods are separated by months or years (e.g., Asher, Aitken, Farooqi, Kurmani, & Baron-Cohen, 2006). On the other hand, the relationship between a specific inducer and concurrent is often inconsistent *across* synesthetes; in other words, while one synesthete might consistently experience a yellow "C", another might consistently experience a green "C".

The heterogeneity of associations between pairs of synesthetes suggests that the relationship between inducer and concurrent is idiosyncratic; indeed, some theories of synesthesia consider between-subject idiosyncrasy to be a defining feature (e.g., Grossenbacher & Lovelace, 2001; Spence & Deroy, 2013). However, a growing number of studies using large samples of synesthetes have demonstrated that some letters are associated with a particular color more often than would be expected by chance (Day, 2004; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005). Consistent associations between letters and colors even exist in non-synesthetes. Simner et al. (2005) demonstrated that non-synesthetes associated some letters with a particular color more often than chance; some of these trends were shared with synesthetes (e.g., both synesthetes and nonsynesthetes associated "A" with red), and some were not (e.g., synesthetes associate "O" with white, whereas non-synesthetes associate "O" with orange). In a cross-linguistic study, English-, Dutch-, and Hindi-speaking non-synesthetes were shown to have consistent color preferences (Rouw, Case, Gosavi, & Ramachandran, 2014). Some of these preferences were found to be similar across languages, and also similar between self-identified synesthetes and non-synesthetes (e.g., again, both synesthetes and nonsynesthetes associated "A" with red). These findings raise the question: if at least some inducer concurrent relationships are not random, are inducer–concurrent relationships in synesthesia driven by universal biases (across languages, and shared between synesthetes and non-synesthetes)? The underlying notion that specific inducer–concurrent relationships might be caused by specific properties of the inducing grapheme is still much debated, but in the past decade a number of studies have demonstrated that several properties can influence inducer–concurrent relationships in both synesthetes and non-synesthetes.

1.1. *Explanatory factors that influence inducer–concurrent relationships*

Below, we review a number of properties that have been shown to influence inducer–concurrent relationships, which we term Explanatory Factors (EFs). These EFs can exert influences on *first-order* associations, causing a grapheme with a particular property to be associated with a particular color, or on *second-order* associations, causing graphemes with similar properties to be associated with similar colors.

1.1.1. *Semantic properties*

Perhaps the most prominent and intuitive explanation of first-order inducer–concurrent relationships invokes semantic associations between a grapheme and a word that begins with that grapheme. Color names appear to strongly influence inducer–concurrent relationships: "R" is typically red, "Y" is typically yellow, and so on (Rich et al., 2005; Simner et al., 2005).

Semantic associations could also influence inducer–concurrent relationships if a grapheme is commonly associated with a word that has a prototypical color; for example, "D" could be brown because "D is for dog", and dogs are often brown. To formally test these hypotheses, Mankin and Simner (2017) used data from a word-generation experiment on non-synesthetic subjects to determine the most common letter-word semantic associations (which they term *index words*), and used data from a separate group of subjects to determine the most prototypical color associated with those index words. They then demonstrated that the prototypical color of index words correctly predicted the most commonly-associated color for 15/26 graphemes, far more than would be expected by chance.

1.1.2. *Visual properties*

Visual features can influence first-order inducer–concurrent relationships. Hubbard, Ambrosio, Azoulai, and Ramachandran (2005) first suggested that synesthetes might associate letters that have curved versus sharp features with "warm" versus "cool" colors, though this observation was not quantified.

Spector and Maurer (2011) propose that the common synesthetic associations between "O" and white, and between "X" and "Z" and black result from tendencies to associate smooth versus jagged shapes with white versus black colors. To avoid the potential confound of semantic associations, they measured the strength of this effect in non-synesthetic, pre-literate children, and demonstrate that these children still associate "O" with white and "X" and "Z" with black significantly more often than expected by chance. The influence of visual shape is also not limited to letters: a study with bi- and trilingual synesthetes showed that the synesthetic colors induced in the non-native language were predicted by visual similarity to words in the native language (Barnett, Feeney, Gormley, & Newell, 2009).

Visual shape has also been shown to induce a second-order effect on inducer–concurrent relationships: letters that share visual features (such as symmetry, curvature, or repeating elements) are associated with similar colors in English-speaking synesthetes (Brang, Rouw, Ramachandran, & Coulson, 2011; Watson, Akins, & Enns, 2012) and German synesthetes (Jürgens & Nikolić, 2012); furthermore, the effect transfers to newly learned graphemes (Jürgens & Nikolić, 2012). Asano and Yokosawa (2013) found that this effect is stronger in English-speaking synesthetes than in Japanese-speaking synesthetes.

1.1.3. *Acoustic properties*

Marks (1975) found that synesthetes with heterogeneous linguistic backgrounds (many of whom were French and German) have consistent associations between vowel inducers and their concurrent colors He tabulated the results from three large scale and 35 small studies, and showed that for each of these datasets the vowel *a* tended to be red and blue, *e* and *i* tended to be yellow and white, *o* tended to be red and black, *u* was usually blue, brown, or black, and *ou* (in French) was brown. By ranking the vowels in acoustic "brightness" (pitch), he showed how the findings could be explained as a generalization of the correlation between visual brightness and visual pitch.

Guillamón (2014) examined, in non-synesthetes, associations between particular sounds and particular colors across different languages. Properties of the vowel spectrum were shown to be associated with certain colors (e.g., the front-mid spectrum is associated with green). Interestingly, the front-open spectrum, where the /a/ or /ɑ/ sounds are located, was found to be associated with red, in Japanese (Miyahara, Amemiya, & Sekiguchi, 2006), Polish and English (Wrembel, 2007), and Arabic (Guillamón, 2014). By using synesthetic vowel sounds manipulated in the two dimensions of a position of an articulatory organ tongue body, Kim, Nam, & Kim (in press) found that low vowels such as [a] are associated with more reddish colors in non-synesthetes.

There is also mixed evidence that acoustic similarity exerts second-order effects: similarly-pronounced letters are associated with similar colors in Japanese (Asano & Yokosawa, 2011) and Korean (Kang, Kim, Shin, & Kim, 2017), but not in English (Watson et al., 2012).

1.1.4. *Ordinal properties*

One property of many languages is that their graphemes have a defined order (alphabet, syllabary, etc.), leading to the possibility that position in the alphabet could affect synesthetic color. Overall, position in the alphabet does not appear to affect synesthetic color (Simner et al., 2005). However, it is possible that ordinal position only influences color for particularly-salient ordinal positions, such as the first or last grapheme in the alphabet. Indeed, Rouw et al. (2014) found that not only was the first grapheme typically red for American, Dutch, and Hindi synesthetes (and also non-synesthetes), Monday (the first day of the workweek in all three cultures) was also associated with red in Dutch, English, and Hindi calendar-color synesthetes (and also non-synesthetes), suggesting that the property of "first" is associated with the color red.

Eagleman (2010) reported that letters in the beginning of the alphabet are associated with colors that are distinct from each other, and letters at the end of the alphabet are associated with colors that are similar to each other; in other words, a second-order relationship between ordinal position and color distinctness. Using a second-order similarity mappings similar to Watson et al. (2012), Asano and Yokosawa (2013) examined determinants of synesthetic colors to Hiragana (a phonetic script in Japanese language). Color distance (and luminance, saturation, hue distance) was predicted most strongly by differences in ordinality (position in grapheme sequence), followed by phonological similarity, and weakest by visual shape similarity and grapheme familiarity.

1.1.5. *Other properties*

Simner et al. (2005) showed in English-speaking synesthetes that grapheme frequency was positively correlated with frequency of color names. Beeli, Esslen, and Jäncke (2007) found, in German-speaking synesthetes, a positive correlation between letter frequency and saturation (though see Simner & Ward, 2008), a finding replicated in Korean by Kim and Kim (2014). Grapheme frequency is related to color luminance, and this effect is also present (though weaker) in non-synesthetes (Smilek, Carriere, Dixon, & Merikle, 2007; Watson et al., 2012).

Grapheme-color relations are also influenced by the ease of generation of the color name or of the color category. Simner et al. (2005) found that non-synesthetes were more likely to associate letters earlier in the alphabet with colors that are easier to generate. Van Leeuwen, Dingemanse, Todil, Agameya, and Majid (2016) further showed that higher-frequency letters are more likely to be associated with colors earlier in the Berlin–Kay color sequence (Berlin & Kay, 1991). The sequence of colors in the Berlin–Kay hierarchy reflects the order in which colors are introduced into languages (Malt & Majid, 2013). They represent a psychological, rather than optical or electromagnetic, view on colors (though see Regier, Kay, & Khetarpal, 2007): the 11 "basic" Berlin–Kay colors are the 11 monomorphemic, monolexemic color categories into which people tend to categorize other colors (e.g., "crimson" a shade of "red", but "red" is not a shade of another color).

Note that the explanations provided above are neither exhaustive nor mutually exclusive. Hung, Simner, Shillcock, and Eagleman (2014) studied the relationship between synesthetic colors and different constituent morphological units of Chinese characters (radicals), showing that hue was determined by the semantic component while luminance was determined by the phonetic component. The effects may also interact: Bargary, Barnett, Mitchell, and Newell (2009) used a multisensory illusion, the McGurk effect, to show that for phoneme-color synesthetes the colors induced by spoken words are influenced by a combination of audio and visual input, and not by auditory or visual input alone.

Furthermore, inducer–concurrent relationships may depend on specific patterns of learning during development. For example, Japanese speakers typically learn the Hiragana script before the Katakana or Kanji scripts; synesthetic colors of Kanji and Katakana graphemes are influenced by phonological similarity to the Hiragana script, rather than by orthographic properties (visual shape, ordinality, etc.) of the Katakana/Kanji script (Asano & Yokosawa, 2012).

1.2. *Explanatory factors might differ between languages*

These findings support the notion that the concept of "letter" is not represented in isolation, but is connected to perceptual representational systems, and that some (but not necessarily all) of these connections might be shared across different languages and cultures. What causes these conscious and unconscious cross-domain connections? The answer to this question is not only interesting in its own right. As elegantly pointed out by Simner (2007), synesthesia is often studied as a sensory phenomenon, but it should also be considered as a psycholinguistic phenomenon. We know that synesthetic associations develop during early childhood (Simner & Bain, 2013), but little is known about how these associations relate to childhood learning mechanisms. The color-to-letter associations obtained in the synesthesia literature offer an extraordinary opportunity to examine relationships between linguistic processes and visual, acoustic, and semantic aspects of language learning.

Some Explanatory Factors might exert more influences in languages with particular properties. For example, the Acoustic EF correctly predicts inducer–concurrent relationships in Japanese Hiragana characters (Asano & Yokosawa, 2011) and Korean Hangul characters (Kang et al., 2017), but not in English letters (Watson et al., 2012). Asano and Yokosawa (2013) propose a model for this discrepancy that invokes the linguistic property of *orthographic depth* – the degree to which graphemes' pronunciation is consistent and predictable. In their model, the feature (they consider acoustic, ordinal, and visual features) of a grapheme that ultimately determines its color is the feature of that grapheme which is most discriminatory or salient during language acquisition. In this framework, the Acoustic EF exerts a stronger influence in Japanese than in English because in Japanese (unlike English), the relationship between a grapheme and its pronunciation is highly consistent, and the syllabary (syllable alphabet) is arranged by sound similarity, both of which are features that would ensure that acoustic properties of graphemes are more salient during the language learning process. More generally, Asano and Yokosawa (2013) propose that, for each grapheme, its most distinctive feature (whether it be ordinal, acoustic, visual, etc.) is the feature that will ultimately influence the grapheme-color association for that particular grapheme.

1.3. *Explanatory factors might differ between graphemes*

From the results reviewed in Section 1.1, it is clear that even within a single language (e.g., English), multiple Explanatory Factors can predict a subset of inducer–concurrent relationships. How do Explanatory Factors interact? Notably, EFs can make both congruent and incongruent predictions about the expected concurrent color of a grapheme. For example, the Semantic EF might predict "V" to be purple (via *violet*) and "X" to be black (via *x-ray*), but the Visual Shape EF might predict "V" and "X" (which share many visual features, such as symmetry, diagonal elements, and no curvature) to share similar colors – i.e., incongruent predictions. On the other hand, the Semantic EF might predict "P" to be pink and "R" to be red, and the Visual Shape EF would predict "P" and "R" to share similar colors – i.e., congruent predictions.

When Explanatory Factors make incongruent predictions, their contributions to a given inducer–concurrent relationship are straightforward to determine. In Mankin and Simner's (2017) data, for example, synesthetes usually experience a purple "V" and a black "X", suggesting that for these particular graphemes the Semantic EF "beats" the Visual Shape EF in a "winner-takes-all" effect. We propose that this is consistent with a within-language application of the model of Asano and Yokosawa (2013): whichever property of a grapheme is most salient is ultimately the property that influences its color. In this framework, the semantic association of "V" with "violet" is more salient than the visual similarity between "V" and "X", and so the Semantic EF influences the color of V.

When Explanatory Factors make congruent predictions, their contributions to a given inducer–concurrent relationship are confounded. For example, one particularly-consistent finding – perhaps the strongest association reported in synesthesia literature – is that English-speaking synesthetes experience the letter "A" as colored red far more often than expected by chance (e.g., Barnett et al., 2009; Day, 2004; Ramachandran & Hubbard, 2001; Rich et al., 2005; Simner et al., 2005). The Semantic (Mankin & Simner, 2017), Acoustic (Kim, Nam, and Kim (in press); Marks, 1975), and Ordinal (Rouw et al., 2014) EFs each predict that "A" should be red, so in a monolingual English dataset it is not possible to determine which EF is responsible for this association (or whether they combine additively – a *cooperative* interaction). For English, each EF offers different, yet equally plausible explanations for the finding that "A" is red. In the present study, we demonstrate that a multilingual dataset allows us to disentangle and contrast different Explanatory Factors of inducer–concurrent relationships. Further, we demonstrate that a language-independent Explanatory Factor best explains our data, suggesting that universal (cross-language) inducer–concurrent relationships do exist in synesthesia.

1.4. *The present study*

Most studies of synesthesia as a psycholinguistic phenomenon have examined synesthetes in only one language (typically English); indeed, the few studies that have tested synesthetes in multiple languages have either used non-native speakers (Asano & Yokosawa, 2013; Shin & Kim, 2014), or have only tested for broad correlations between languages (Rouw et al., 2014). Studying inducer–concurrent relationships with native speakers of different languages might enable researchers to disentangle the effects of EFs that make congruent predictions about an inducer–concurrent relationship. For example, while the Semantic and Ordinal EFs both predict English “A” to be red, in Spanish, the Semantic EF would predict “A” to be blue (via *azul*), whereas the Ordinal EF would still predict “A” to be red.

To illustrate the methodological advantages of multilingual synesthesia research, we combine previously-collected synesthetic associations from native speakers of five different languages into a single dataset, and derive and test predictions that four different Explanatory Factors make about the color of graphemes in Spanish-, Dutch-, Japanese-, and Korean-speaking synesthetes. Specifically, we attempt to discover which Explanatory Factor(s) causes the English “A” to be associated with the color red, by comparing the predictions that each of these EFs make about associations in the other languages in our dataset.

Our choice of languages was driven by two factors: data availability, and the idiosyncratic properties of each language. While we expected semantic associations to differ between most languages, the influence of some EFs can only be disentangled with certain languages. Dutch is closely related to English (it is also part of the Germanic branch of the Indo-European language family), and shares many linguistic properties with English. However, including Dutch in this study allows us to contrast two types of acoustic EF: the phoneme of the English letter “A” is [aː] (in IPA), similar to Dutch; however, the name of the letter A is very different in the two languages: the letter is called [aː] in Dutch, but [eɪ] in English (furthermore, the sound [eɪ] is in Dutch the name of the letter “E”). Spanish shares the same alphabet as Dutch and English, but is otherwise quite different. Spanish has a shallow, transparent orthography (Bravo-Valdivieso & Escobar, 2014; Seymour, Aro, & Erskine, 2003) and a smaller vowel inventory (Bradlow, 1995), so the Acoustic EF might be expected to play a larger role in determining inducer–concurrent relationships. Finally, Spanish is a Romance language rather than a Germanic language, so we might expect semantic associations to differ more than between English and Dutch; indeed, recent research suggests that different linguistic backgrounds (Spanish *vs* English) lead to language-dependent cross-modal associations in non-synesthetes (Fernandez-Prieto, Spence, Pons, & Navarra, 2017). Korean is one of the few commonly-spoken languages in which the grapheme encoding “A” is not the first letter of the alphabet (the first letter of the Korean Hangul alphabet roughly corresponds to [g~k]), enabling us to disentangle the ordinal EF. However, in Korean the Visual and Acoustic EFs are confounded, because Hangul is a featural alphabet – similar-shaped graphemes encode similar-sounding phonemes. The last language in our dataset, Japanese, allows for us to completely disentangle the visual EF: the Japanese Hiragana syllabary is visually quite different from the Roman alphabet, and in Japanese there is no relationship between the visual form of a grapheme and its pronunciation.

2. Experiment 1: replicating the result that “A is often red”

The propensity for English-speaking grapheme-color synesthetes to associate “A” with the color red has been formally tested for British (Simner et al., 2005) and Australian (Rich et al., 2005) synesthetes, but not for American synesthetes (however, see Day, 2004 for a descriptive report). We first sought to replicate these results in our American sample.

2.1. *Methods*

2.1.1. *Subjects*

Data were previously collected from 82 self-described synesthetes. All participants were fluent English speakers. Synesthetes were recruited via fliers posted on the UCSD campus, as well as similar ads on the web. All participants gave informed consent prior to the experiment.

2.1.2. *Data acquisition and preprocessing*

Participants were directed to the Eagleman Synesthesia Battery (synesthete.org), a standardized battery for Synesthesia (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007). Each subject used a color picker (256 × 256 × 256 possible colors) to choose the color they experience for each grapheme 3 times. We excluded subjects whose average sum Euclidean distance in CIELuv between 3 repeated measures was greater than 135 (following the recommendation from Rothen, Seth, Witzel, & Ward, 2013); by this criterion, we excluded 28 subjects with insufficient color consistency scores. Additionally, we excluded any subjects that did not experience synesthetic colors for at least 50% of graphemes; by this criterion, we excluded 7 subjects, yielding data from a total of 47 synesthetes. From each synesthete's data, we furthermore removed graphemes for which the synesthete did not choose a consistent color (CIELuv distance was greater than 135). Finally, we collapsed across the 3 repeated measures of each grapheme by computing the average (in CIELuv space) of the reported colors, obtaining a single CIELuv color for each grapheme, for each synesthete.

We categorized the color-grapheme associations of the 47 English-speaking synesthetes using the 11 basic color terms of Berlin and Kay (1991). For each association, we calculated the nearest of the 138 standardized W3C (World Wide Web Consortium) colors[2] using the CIE 2000 color difference formula (Sharma, Wu, & Dalal, 2005). For each W3C color, we instructed three blind coders to indicate its basic Berlin and Kay (1991) color category (raters agreed on 96% of matches; when there was disagreement, the modal color choice was used). In

[2] We first transformed our data into the 138-color W3C color space because (i) it was impractical for blind coders to determine the Berlin–Kay color of every single color experienced by all synesthetes, and (ii), Japanese synesthetes used the W3C color space in their original test, and we wanted to ensure that the rest of our data was as equivalent as possible.

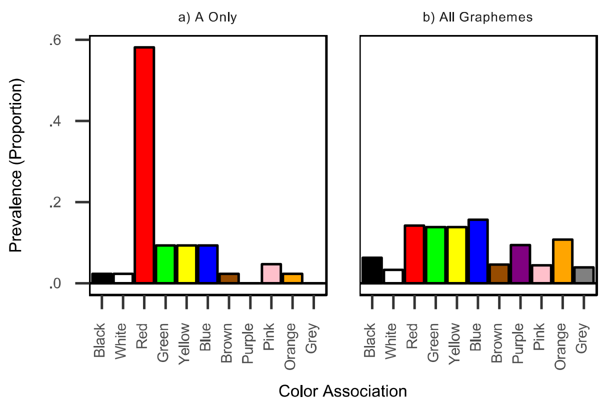

Fig. 1 – Proportion of associations in each color category for "A" (a) or all graphemes (b).

this way, all grapheme-color associations were mapped on to the 11 basic color categories.

2.2. *Results*

Fig. 1 depicts the proportion of subjects for which the letter "A" is associated with each color category (Fig. 1a) and the same statistic for all graphemes (Fig. 1b). It is visually obvious that "A" is unusually likely to be red. This is not a proper test however, as it does not quantitatively contrast the color distribution of the letter A with the distribution of all colored graphemes. To quantify this observation we perform a chi-squared goodness-of-fit test, with the null hypothesis that the observed counts for the letter "A" come from the probability distribution of all graphemes (i.e., that the distributions in Fig. 1a and b are not different), and follow up this omnibus test with post-hoc cellwise tests on the standardized Pearson residuals, using the methods described in MacDonald and Gardner (2000).[3]

Given a set of k observed counts $O_i|_{1\leq i\leq k}$, sample size n, and expected probability p_i, the chi squared statistic for a goodness-of-fit test can be written in the form $\chi^2 = \sum_{i=1}^{k}(O_i - np_i)/np_i$. The standardized Pearson residual z for cell i is then $z_i = (O_i - np_i)/\sqrt{np_i(1-p_i)}$. Standardized Pearson residuals are standard normal distributed (Agresti, 1996), and thus statistical significance can be assessed using a z-test. Bonferroni-corrected z-tests of standardized Pearson residuals yield appropriate (though slightly conservative) Type I error rates, and are the preferred cellwise post-hoc test for omnibus chi-squared tests (MacDonald & Gardner, 2000).

[3] This approach differs only slightly from the binomial test approach used by Simner et al. (2005); it uses the normal approximation to the binomial distribution but is otherwise identical. The benefits of using the normal approximation are that an omnibus chi-squared statistic can be calculated that characterizes a grapheme's overall deviation from the expected distribution of grapheme-color associations, and also that it yields a single statistical significance value across colors, graphemes, and languages, enabling more intuitive visualization (e.g., Fig. 2). To verify that our choice of statistic did not alter our results, we also analyzed our data using Simner et al.'s (2005) method, and obtained the same result in every experiment.

As expected, the omnibus chi-squared statistic is highly significant, $\chi^2 = 70.958$, $p < 0.0001$ (p value calculated using the Monte Carlo method described in Hope, 1968, with 100,000 replications). To test whether this effect is explained by the propensity of red "A", we examined the standardized Pearson residuals using the method in MacDonald and Gardner (2000). We applied a Bonferroni correction procedure (corrected for the 11 Berlin–Kay color categories), yielding a corrected alpha of $\alpha = 0.0045$ and a critical value $z = 2.61$. Fig. 2 depicts the standardized Pearson residuals, and the black dotted lines depict the critical value (threshold for statistical significance). As expected, the residual for red was highly significant, $z = 8.24$, $p < 0.0001$. No other residual was statistically significant (all other $p > 0.05$).

2.3. *Discussion*

We demonstrate that, for American English-speaking synesthetes, "A" is red more often than would be predicted by chance (if "A" were no different than other graphemes). This cannot be explained by an overall tendency for synesthetes to experience letters as red, because we used the overall distribution of synesthetic associations as the null hypothesis. It also cannot be explained by an overall tendency for synesthetes to experience primary colors for early letters in the alphabet, as reported by Eagleman (2010): synesthetes were no more likely than chance to associate "A" with blue, green, or yellow. Our results are consistent with those of Simner et al. (2005) and Rich et al. (2005), and extend their findings (in British and Australian English-speaking synesthetes, respectively) to an American sample.

3. Experiment 2: why is "A" red?

Why are English-speaking synesthetes likely to associate "A" with red? The letter "A" has numerous properties, including its shape, its sound, its ordinal position in the alphabet, and its

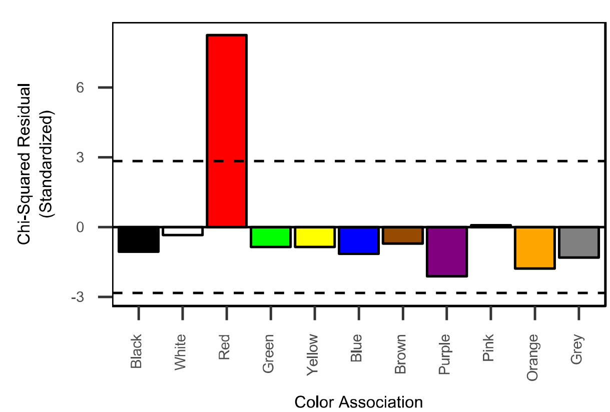

Fig. 2 – The standardized residuals of a chi-squared goodness of fit test of the hypothesis that the observed associations for "A" (Fig. 1a) come from the overall distribution of colors (Fig. 1b). The dotted line depicts the $p < .0045$ threshold for significance (alpha level adjusted from .05 using Bonferroni method).

semantic associations. Each of these potential Explanatory Factors likely explains some subset of grapheme-color associations (as noted in Section 1.3 in the introduction), but in a monolingual English dataset it is not possible to determine which EF accounts for the propensity for the red "A". However, these hypotheses make distinct predictions about patterns of synesthetic association in languages other than English. Using a multilingual dataset, we derive predictions made by the Acoustic, Visual Shape, and Ordinal EFs, and determine if any EF makes correct predictions in all languages.

3.1. Methods

3.1.1. Subjects

American synesthetes were the same as in Experiment 1. 156 potential Dutch synesthetes were recruited in several ways, including through testing psychology students, posting on synesthesia forums, and through exposure of the research through television interviews and radio shows. 40 Spanish synesthetes were identified by using Artecittá Foundation Questionnaire (for a complete description of subjects recruitment, please see Melero, Peña-Melián, & Ríos-Lago, 2015). Thirteen Korean synesthetes were identified using the Korean Synesthesia Questionnaire (for a complete description of subjects recruitment, see Kim & Kim, 2014) and online using the Synesthesia Battery (Eagleman et al., 2007). Twenty-seven Japanese self-described synesthetes were recruited via a website (for more details, see Asano & Yokosawa, 2011). All participants gave informed consent prior to the experiment.

3.1.2. Data acquisition and preprocessing

English (American) data was the same as in Experiment 1. Spanish and Dutch synesthete associations were acquired using the Eagleman Synesthesia Battery (Eagleman et al., 2007). Korean data for eight subjects was acquired using a translated version of the synesthesia test derived from the TexSyn Toolbox for Matlab, that was functionally identical to the Synesthesia Battery (Eagleman et al., 2007); data for the other five subjects was acquired by asking synesthetes to adjust the color of a square to match each inducing grapheme, using the color palette embedded in Microsoft Powerpoint. Dutch and Spanish synesthete data, and the data from the group of Korean subjects who completed a Korean translation of the Eagleman Battery, was preprocessed as in Experiment 1. Japanese synesthetes selected colors using a palette of the 138 named W3C colors (see Supplemental Text 1, Section S1 for additional details); this data was preprocessed using the procedures in Experiment 1 except for the transformation to W3C space. After preprocessing, the final dataset included 47 English, 110 Dutch, 32 Spanish, 27 Japanese, and 12 Korean subjects.

3.1.3. Hypotheses

In this experiment, we tested the cross-linguistic predictions made by three different Explanatory Factors that each predict the English "A" to be red: an Acoustic EF ("A" is red because of its sound; Marks, 1975), a Visual Shape EF ("A" is red because of its shape; Hubbard et al., 2005), and an Ordinal EF ("A" is red because it is the first letter of the alphabet; Rouw et al., 2014). The Semantic EF will be tested in Experiment 3.

3.1.3.1. Acoustic EF. If "A" is red because it encodes the phoneme /aː/ (in IPA), as hypothesized by Marks (1975), then the letter that encodes the phoneme /aː/ in other languages (Dutch: "A", Spanish: "A", Japanese: "あ", Korean: "ㅏ") should also be red more often than chance. Note that hypothesis is also confounded with the visual hypothesis in Dutch and Spanish, and the ordinal hypothesis in Dutch, Spanish, and Japanese. Therefore, the most crucial prediction to test is whether or not the Korean "ㅏ" is red, since the *only* feature it shares with English "A" is its acoustic similarity.

Another possibility is that the *name* of the letter – rather than the phoneme it typically encodes – causes "A" to be red. In English, the letter name of "A" is pronounced as the diphthong [eɪ], which is identical to the Dutch letter "E" ([eɪ]), and shares acoustic features with the Spanish letters "E" ([e]) and "I" ([ɪ]) (Collins & Mees, 2003; Roach, Hartman, Setter, & Jones, 2006). If English "A" is red because it encodes the phoneme /eɪ/ (or because this is how the name of the letter is pronounced in English), then Dutch "E", Spanish "E"/"I", Hiragana "え"/"い", and Korean "ㅔ"/"ㅣ" should be red more often than chance.

3.1.3.2. The visual hypothesis. The hypothesis that "A" is red because of some feature of its visual shape (e.g., Hubbard et al., 2005) is confounded with other hypotheses in Dutch and Spanish, but makes distinct predictions about the color of letters in Japanese and Korean synesthetes, since Japanese and Korean do not use the Roman alphabet. Previous research on English-speaking synesthetes demonstrates that a shape-similarity measure derived from the 11-dimensional shape classification system of Gibson (1969) successfully predicts some aspects of grapheme-color associations in English-speaking synesthetes (e.g., Brang et al., 2011; Watson et al., 2012). In Gibson's system, letters are characterized by the presence or absence of 11 different visual features (symmetry, repetitive elements, curvature, etc.); the more shared visual features, the more similar the letters. We quantified the visual similarity of Hiragana and Hangul graphemes to the English grapheme "A" using the same shape-similarity measure as these previous studies. By this measure, the most visually-similar Hiragana grapheme to the English "A" is "た" (pronounced [ta]), and the most visually-similar Hangul grapheme to the English "A" is "ㅈ" (pronounced [dʑ]). If "A" is red due to its visual properties, then Hiragana "た" and Hangul "ㅈ" should be red more often than predicted by chance.

3.1.3.3. The ordinal hypothesis. The hypothesis that "A" is red because it is the first letter of the alphabet (Rouw et al., 2014) is confounded with other hypotheses in Dutch, Spanish, and Japanese, but makes a distinct prediction in Korean: the first grapheme in the Hangul (Korean) alphabet is "ㄱ", encoding [g~k]. This grapheme shares no features with the English "A" other than its ordinal position. If "A" is red because it is the first letter of the alphabet, then Hangul "ㄱ" should be red more often than predicted by chance.

3.2. Results

We tested each hypothesis using the same methods as Experiment 1: a series of post-hoc cellwise z-tests on the standardized Pearson residuals of a series of chi square goodness of fit tests. The null hypothesis in each case was that the distribution of color associations for the grapheme of interest (the "A"-like grapheme in each language that each EF predicted should be red) was not different from the distribution of color associations for all graphemes within each language. Fig. 3 depicts the red residuals for graphemes predicted by each EF to be red (see Supplemental Text, Section S2, Fig. S1, for the full set of residuals), and Table 1 depicts the results of each test. An EF has made a correct prediction in a language if the red residual is significantly larger than expected. The Ordinal EF was the only Explanatory Factor which correctly predicted the red grapheme for all languages.

3.3. *Discussion*

The only Explanatory Factor that makes correct predictions in all five languages is the Ordinal EF: synesthetes associate the first letter of the alphabet/syllabary with red. Every other EF made predictions that were not supported by our results. The Acoustic EF predicted that the Korean "ㅏ" should be red, however this was not the case: it not was associated with any color significantly more often than predicted by chance. The "modified" Acoustic EF (letter name, rather than pronunciation) made numerous predictions about which graphemes should be red, none of which were consistent with our data (some of these graphemes were not associated with any color significantly more often than predicted by chance; others were significantly likelier to be green, yellow, or blue, but not red). The Visual Shape EF predicted that the Hiragana "た" and Hangul "ㅈ" should be red, but neither of these graphemes were associated with any color significantly more often than predicted by chance. On the other hand, the Ordinal EF predicted that Korean "ㄱ" (a grapheme that shares no visual or acoustic feature with "A") should be red more often than predicted by chance, and this is consistent with our results.

We have found an ordinal-based, language-independent "rule" of grapheme-color associations: the first letter of the synesthete's native alphabet/syllabary is associated with red significantly more often than predicted by chance. It is important to note that we do not seek to claim that acoustic or visual properties do not explain *any* synesthetic associations. Indeed, we also see evidence in our data of a shape-based language-independent rule: consistent with studies of shape–color associations in pre-verbal infants (Spector & Maurer, 2011), we find that the annulus shape ("O" in English/Dutch/Spanish and "ㅇ" in Korean; note that Korean "ㅇ" does not share acoustic, ordinal, or semantic features with "O", only visual shape) is associated with white significantly more often than predicted by chance (Supplemental Text, Section S2, Fig. S2). In other words, various language-independent and language-dependent Explanatory Factors may each contribute to the overall pattern of inducer–concurrent relationships, and which EF contributes to a particular concurrent's color may depend on the salience of various features of its inducing grapheme (e.g., the "first-ness" of "A" is particularly salient, and the roundness of "O" is particularly salient). By comparing grapheme-color associations across several languages, it is possible to determine *which* EF is the most likely cause for a *particular* grapheme-color association. Furthermore, it allows to show that at least some effects are not language-specific but seem universal. We have demonstrated one such result: our findings, taken together, offer strong evidence that the English "A" is red because it is the first grapheme in the alphabet.

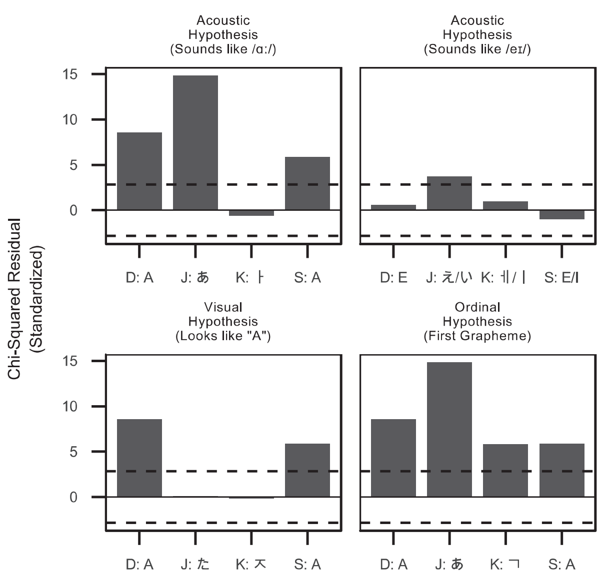

Fig. 3 – The standardized Pearson residuals for the red residual of a chi-squared test of the distribution of colors for the grapheme that each Exploratory Factor (Acoustic, Visual, Ordinal) predicts should be red. The dotted line depicts the $p < .0045$ threshold for significance (alpha level adjusted from .05 using Bonferroni method). For each language (D: Dutch, J: Japanese, K: Korean, S: Spanish), an EF makes a valid prediction if the depicted residual is more significant than chance. If an EF is supported in every language tested (all four residuals are significant, a "universal" rule), we conclude that it is the most likely cause of the "English A is red" effect.

4. Experiment 3: semantic associations

Mankin and Simner (2017) suggest that the color of letters might be influenced by an *index word* (a commonly-generated word beginning with the grapheme) that has a prototypical color. In other words, for English speakers, "A" could be red more often than chance because "A" is often associated with the word "apple", and apples are prototypically red. Our result from Experiment 2 could be confounded if index words for the first grapheme in the other languages in our dataset were all (coincidentally) associated with red. In order to exclude this possibility, we administered a survey to non-synesthetic native speakers of each language, in which we asked them to generate words that came to mind when they thought of the first grapheme in their language, and a survey to a separate group of non-synesthetic native speakers of each language, in which we asked them to generate the prototypical color of each of the words that were chosen more than once by the first group. We then used the framework of Mankin and

Table 1 – Significance tests for Hypotheses I–IV.

Language	I. Acoustic (/a:/)	II. Acoustic (/eɪ/)	III. Visual	IV. Ordinal
Dutch	$z = 8.59^{****}$	$z = .60$	$z = 8.59^{****}$	$z = 8.59^{****}$
Spanish	$z = 5.86^{****}$	$z = -.99$	$z = 5.86^{****}$	$z = 5.86^{****}$
Japanese	$z = 14.84^{****}$	$z = 3.73^{**}$	$z = .080$	$z = 14.84^{****}$
Korean	$z = -.59$	$z = .96$	$Z = -.14$	$z = 5.79^{****}$

Significance tests for the red residual of a chi-squared goodness of fit test of each letter, with the null hypothesis of an equal color distribution. Asterisks indicate Bonferroni-corrected p-values: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$, $^{****}p < .0001$. For a hypothesis to be supported by our results, the entire column of cells should be statistically significant.

Simner (2017) to determine whether the tendency for the first grapheme to be red in each language could be explained by a commonly-generated index word in each language that is judged to be prototypically-red.

4.1. Methods

4.1.1. Subjects

For the word generation experiment, we recruited native English, Dutch, Spanish, Japanese, and Korean speakers. We screened these subjects for different types of synesthesia including grapheme-color synesthesia using a questionnaire (adapted from the Eagleman Synesthesia Battery; Eagleman et al., 2007). We excluded any subject that was a potential synesthete (Hancock's hypothesis suggests that word associations *cause* specific grapheme-color associations; if these subjects were synesthetes, their synesthesia might cause their word associations, so the direction of causality could not be determined). After filtering based on this criterion, our dataset included 18 American, 26 Dutch, 26 Spanish, 14 Japanese, and 18 Korean subjects.

4.1.2. Procedure

We created an experiment using the Qualtrics survey software (Qualtrics, Provo, UT). All instructions and experiment material was translated into the appropriate language (English, Dutch, Spanish, Japanese, or Korean). For each grapheme in the subject's native language, the target grapheme was presented, and the subject was instructed to type the first five words that came to mind that began with the target grapheme. The experiment was unspeeded, but participants were told to answer as quickly as possible, and to choose the first words that came to mind. Target graphemes were presented in random order.

4.2. Results

We defined an “index word” using the same criterion as Mankin and Simner (2017): the top three generated words for each grapheme. For every index word, an additional five non-synesthetic blind coders (five for each language) classified each word by its prototypical Berlin–Kay color, or indicated that the word had no prototypical color. For each combination of index word and Berlin–Kay color, we multiplied the proportion of subjects who generated the word by the proportion of blind coders who chose that color as prototypical. These proportions were then normalized to sum to 1 (i.e., the assumption that the Semantic EF completely explained the observed color of the first grapheme); Fig. 4 depicts the colors predicted for each language.

Qualitatively, the Semantic EF clearly predicts a red first grapheme in English (via “apple”) and Japanese (via ”赤” [aka] – the color red), but predicts that colors other than red are more likely for Dutch, Korean, and particularly Spanish. In particular, the Semantic EF predicts Dutch “A” to be brown (via “aap” – ape), Spanish “A” to be blue (via “azul” – blue), and Korean “ㄱ” to be purple (via “가지” – eggplant). However, none of these predictions appear consistent with our dataset.

To quantify this observation, we repeated our chi-square tests from Experiments 1 and 2, but used the frequencies predicted by the Semantic EF as the null hypothesis (instead of the average observed color distribution). The standardized Pearson residuals of this test (Fig. 5) indicate the degree to which the observed color associations deviate from those predicted by the Semantic EF. The English “A” and Japanese “あ” are red as often as would be expected under the Semantic EF (both $p > .05$). However, in Dutch, Korean, and Spanish, the first grapheme is red significantly more often than would be expected under the Semantic EF (Dutch: $z = 4.15$, $p < .001$; Korean: $z = 2.77$, $p = .039$; Spanish: $z = 7.57$, $p < .0001$). Furthermore, under the Semantic EF, Dutch synesthetes are significantly less likely than expected to associate “A” with brown ($z = -8.38$, $p < .0001$), Japanese synesthetes are significantly less likely to associate “あ” with orange ($z = -2.71$, $p = .034$), and Korean synesthetes are marginally less likely to associate “ㄱ” with purple ($z = -2.65$, $p = .056$).

4.3. Discussion

We replicated Mankin and Simner's result in our English dataset: “apple” was by far the most-generated English word that began with “A”, and most blind coders indicated that apples are prototypically red. The Semantic EF could also explain the red “あ” in Japanese (via ”赤” [aka] – the color red). However, we found no likely candidates for index words that could explain the association of Korean “ㄱ”, Spanish or Dutch “A” with red. The Dutch word for “apple” (“appel”) also begins with “A” and is frequently-generated, but it is less-frequently-generated than “ape” (“aap”, associated with brown), and – unlike American subjects – Dutch subjects disagree about the prototypical color of apples (60% red, 40% green). The Spanish index word for “love” (“amor”) is associated with red by 40% of Spanish subjects, but was generated by only 19% of subjects (in contrast with index words in other languages, for which there was more agreement). Additionally, it seems to us unlikely that such a metaphorical association would develop in

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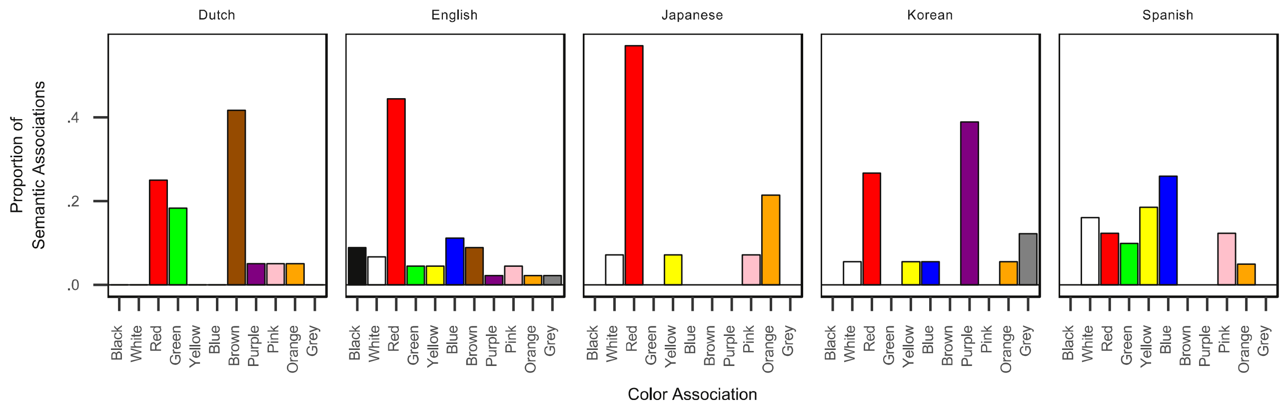

Fig. 4 – The normalized proportion of color responses for the index words in each language. These proportions correspond to the null hypothesis that all inducer–concurrent relationships are explained by the Semantic EF.

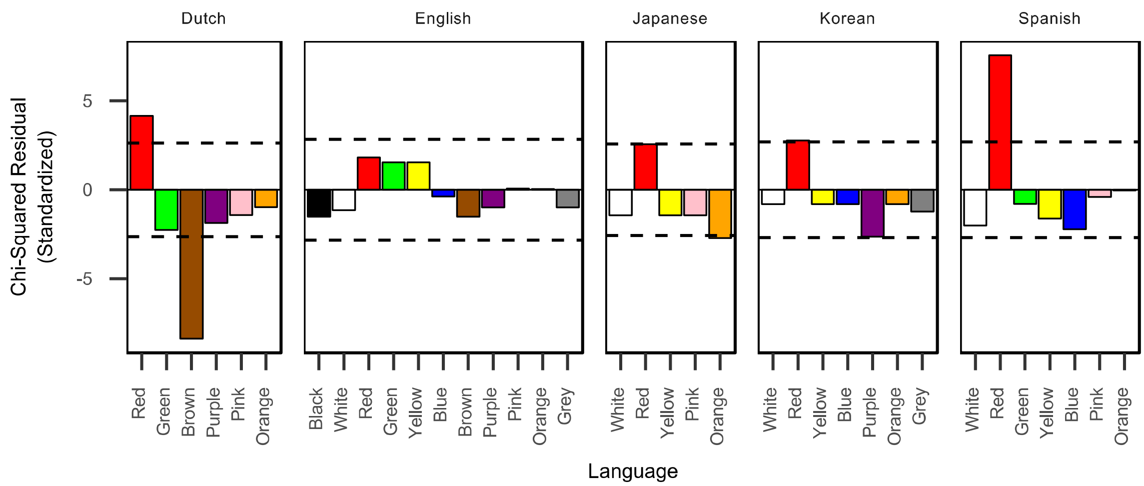

Fig. 5 – The standardized residuals of a chi-squared goodness of fit test of the hypothesis that the observed associations for the first grapheme come from the distribution of associations predicted by the Semantic EF. The dotted line depicts the Bonferroni-corrected significance threshold for an alpha of .05. If the red residual is significantly larger than chance, this means that the first grapheme is red more often than would be predicted by the Semantic EF.

early childhood; indeed, in Mankin and Simner's (2017) study, "love" is the most frequently generated index word and is associated with red, but their synesthetes do not associate "L" with red.

Our results suggest that when the Ordinal and Semantic EF predict different colors for the first grapheme, only the predictions of the Ordinal EF are correct across all languages. In particular, there are several frequently-generated, highly-imageable words in our dataset that the semantic hypothesis predicts should induce the Spanish "A" to be blue ("azul"/"blue") or yellow ("amarillo"/"yellow"), Dutch "A" to be brown ("aap"/"ape"), and Korean "ㄱ" to be purple ("가지"/"eggplant"), but none of these predictions were significant in our dataset. In fact, Spanish "A", Dutch "A" and Korean "ㄱ" were (respectively) blue/yellow, brown and purple *less* often than the average grapheme, though not significantly so. In other words, we find no evidence that these index words influenced the color of the first grapheme in Spanish, Dutch, and Korean.

One other possibility is that since the Semantic and Ordinal EFs make congruent predictions in English (via "apple") and Japanese (via "red"), the likelihood that these graphemes are red is higher (i.e., an *additive* interaction between EFs). However, the effect size of the red first grapheme in Korean and Spanish is stronger than in English (Supplemental Text, Section S3, Fig. S3), so we see no evidence in our data that the Semantic EF can exert an additive influence on the color of the first grapheme.

As with Experiment 2, we do not suggest that the Semantic EF is *generally* false, only that it is not the most likely explanation for the *particular* grapheme-color association of the red "A". Indeed, our English data is broadly consistent with Mankin and Simner's (2017) results (e.g., our data is consistent with the Semantic EF prediction for "Y" – yellow), and we also see potential examples in our data of grapheme-color associations derived from semantic associations in Spanish (e.g., "R" is red, via *rojo* – "red"), Dutch (e.g., "R" is red, via *rood* – "red"), Japanese (e.g., "そ" is blue, via そら – "sky"), and Korean (e.g., "ㄷ" is brown via 다람쥐 – "squirrel"). We suggest that the Semantic EF influences these graphemes' colors because their semantic associations are their most salient feature. On the other hand, the Ordinal EF influences the first grapheme's color, because its "first-ness" is more salient than its semantic associations.

In sum, the Semantic EF does not correctly predict the color of the first grapheme in Spanish, Dutch, or Korean, whereas the Ordinal EF correctly predicts the color of the first grapheme in every language tested. Thus, we still find the Ordinal EF ("the first grapheme is red") a more parsimonious explanation for why the English "A" is red.

5. Experiment 4: distinctness of the first grapheme

The Ordinal EF (which our data supports as the most likely explanation for why "A" is red) explains why the first grapheme is a consistent color, but not why the first grapheme is *red*. Why red, and not some other color?

The color red has several properties that might cause it to be considered "distinct", or "special". First, red is typically the most basic color term acquired by a culture, after "dark" and "light" (Berlin & Kay, 1991). Second, red may have been an important signal color in our evolutionary past, indicating ripe fruit (e.g., Mollon, 1989), dominance (e.g., Pryke, Andersson, Lawes, & Piper, 2002; Setchell & Jean Wickings, 2005) or estrus (e.g., Dixson, 1983). Third, at maximum excitation purity, red has a higher chroma than other colors (red is very far from white in uv chroma space); in other words, saturated red is perceived as particularly "colorful" or "distinct". This third property of red need not be independent of the first two: there is evidence that the order of acquisition of Berlin and Kay's basic color terms can be derived solely from the properties of color vision (Regier et al., 2007), and this property of color vision could have resulted from an evolutionary need to more easily distinguish red.

The grapheme in the first ordinal position (in English, "A") is also "distinct": in ordinal position judgment tasks, subjects indicate the ordinal position of the first grapheme more accurately and more quickly than that of any other grapheme (Jou & Aldridge, 1999). One explanation for the association of the first grapheme with red, then, is that the first member of a sequence is "distinct" or "special", red is a "distinct" or "special" color, and thus the first grapheme is associated with red. The "distinctness" explanation generates testable and specific hypotheses about synesthetes' color associations. If the tendency for the first grapheme to be red is due to the tendency for the first grapheme to be distinct, then the color of the first grapheme should be distant in color space from other letters (Prediction 1).

This prediction, if true, does not prove that the "distinctness" route explains the red first grapheme, since red graphemes are generally likely to be distant (since red has a high possible chroma compared to other colors). To eliminate this confound, we can test two additional predictions. Prediction 2: first graphemes that are not red should *still* be more distinct than expected (for example, if a synesthete's first grapheme is blue, then that synesthete's other graphemes should be associated with colors that are distant in uv space from blue). Prediction 3: first graphemes that are red should be more distinct than other graphemes that are red.

5.1. Methods

We used the W3C color data from Experiment 2 (before the preprocessing step in which it was reduced to Berlin–Kay colors) to test these hypotheses. First, we computed the average pairwise distance in the uv chromaticity plane between all grapheme pairs in each language. On average, the pairwise distances between the first grapheme and other graphemes were clearly larger than other pairwise distances in the data (see Supplemental Text, Section S4, Figs. S4 and S5 for visualizations).

To quantify this observation, we computed the average pairwise distance between the first grapheme and other graphemes, and then generated a non-parametric reference distribution ($N = 100{,}000$) using Monte Carlo resampling (grapheme labels were scrambled within subject, i.e., a null hypothesis of exchangeability). By comparing the observed distance to the reference distribution of distances under the null hypothesis, we can calculate a p-value that represents the likelihood that the observed distance came from the reference distribution. To test Predictions 2 and 3 (that the distinctness effect would be present in the subset of non-red graphemes only, and also present in the subset of red graphemes only), we repeated this analysis on subsets of the data in which red or non-red graphemes (respectively) were removed.

For all five languages, the first grapheme was significantly more distant in uv chromaticity space than other graphemes (Fig. 6a: Prediction 1; all $p < .0001$). For all languages except Korean, the first grapheme was significantly more distant than other graphemes even when the data was restricted to only non-red graphemes (Fig. 6b: Prediction 2; Dutch: $p < .0001$, English: $p < .0001$, Japanese: $p < .001$, Korean: $p = .37$, Spanish: $p = .0074$) or to only red graphemes (Fig. 6c: Prediction 3; all $p < .0001$ except for Korean). When the data was restricted to red graphemes only, in Korean the first grapheme was less distinct than predicted (Fig. 6c; Korean: $p = .010$) (Fig. 6).

5.2. Discussion

We find strong evidence for the first prediction: the first grapheme is statistically-significantly more distinct than predicted by chance in every language we tested. In other words, the color of the first grapheme is distinct (distant in uv space) from the colors of all other letters. We find mixed evidence for the second and third predictions: when the first grapheme is not red, it is still more distinct than other non-red graphemes; when the first grapheme is red, it is more distinct than other red graphemes. We obtained this result in all languages except Korean.

One likely explanation for the null result in Korean is that it is an artifact of the small sample size of our Korean data: only four of our Korean subjects have non-red "ㄱ", so this test is very underpowered. However, using the framework of Asano and Yokosawa (2013), it is also possible that in Korean other EFs are more salient than the ordinal EF. For example, the exceptional amount of structure in the orthography-to-

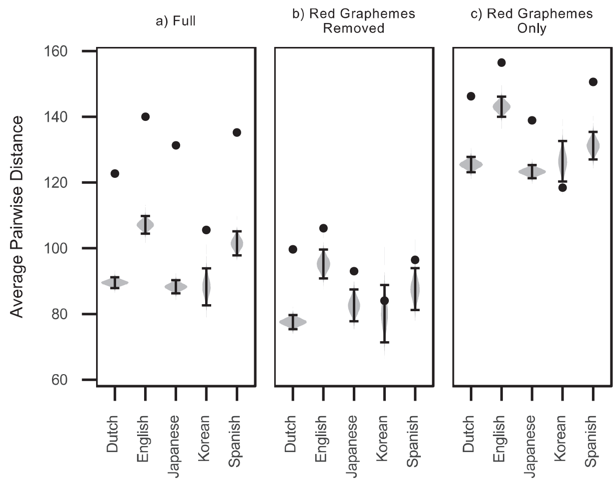

Fig. 6 — Results of Monte Carlo permutation tests ($N = 100{,}000$), with the null hypothesis that grapheme labels are exchangeable within-subject. The black dot depicts, for each language, the average pairwise Euclidean distance between the first grapheme and other graphemes in the uv plane of CIELuv space. The gray density plot and black error bars depict the reference distribution and 95% confidence interval of the expected value of this statistic, generated using Monte Carlo sampling. Fig. 6a depicts the results of this test for the full dataset. Fig. 6b depicts the results of this test for a subset of the dataset, in which all red graphemes were removed. Fig. 6c depicts the results of this test for a subset of the dataset, in which all non-red graphemes were removed.

phonology relationship in Hangul (Hangul is the only commonly-used featural orthography) might lead the Acoustic EF to play a larger role (indeed, this has been reported in Kang et al., 2017). If the Acoustic EF causes graphemes encoding sounds similar to "ㄱ"(/g/) to be associated with a similar color to "ㄱ", then the distinctiveness of "ㄱ"(/g/) would be reduced.

6. General discussion

We replicated the finding that, for English-speaking synesthetes, "A" is red much more often than would be expected by chance. Using a five-language dataset, we tested a number of different hypotheses that sought to explain why the English "A" is red using different Explanatory Factors (visual shape, acoustic, semantic, ordinal). Only the Ordinal EF ("the first grapheme in the alphabet/syllabary is often red") was strongly supported in all five languages in our dataset, and all other hypotheses made predictions that were not consistent in at least one language.

Next, we sought to test the hypothesis that the first grapheme is red because it is distinct (distant in chromaticity space). We found that the first grapheme is statistically-significantly more distinct than predicted by chance in every language we tested; furthermore, non-red first graphemes are statistically-significantly more distinct than other non-red graphemes every language we tested except Korean, and red first graphemes are statistically-significantly more distinct other red graphemes in every language we tested except Korean. The null results in Korean might be caused by an underpowered sample, but might also indicate that a highly-salient EF in Korean (such as the Acoustic EF) causes other graphemes to share a similar color with the first grapheme. In the future, given a larger sample size of Korean synesthetes, these explanations could potentially be disentangled. At present, our results suggest (but do not prove) that the "distinctness" EF could be the mediating factor in the relationship between the first grapheme and the color red.

Our research suggests that the Ordinal EF, rather than the Visual, Acoustic, or Semantic EF, influences the color of the red "A". Why should the Ordinal EF "win" in this instance? We believe Asano & Yokosawa's developmental model – that "synesthetic color highlights the most discriminating feature of each grapheme, which people (both synesthetic and non-synesthetic) rely on when learning graphemes" (Asano & Yokosawa, 2013) – can explain our results. In this framework, the first grapheme is influenced by the Ordinal EF because its ordinality is particularly distinctive; in other words, the "first-ness" of "A" is more salient than any other property. On the other hand, the "fifteen-ness" of "O" is surely less salient than the roundness of "O", so it is not surprising that the Visual Shape EF influences its color. It might be possible to formulate a statistical model which incorporates parameters for both between-language differences in salience (e.g., the Acoustic EF is more salient in orthographically-transparent languages) and within-language differences in salience (e.g., "first-ness" is more salient than "second-ness"). Such a model could yield a compelling answer to the question of the degree to which there are language-independent influences on inducer–concurrent relationships in grapheme-color synesthesia.

In addition to its psycholinguistic predictions, this framework can also be used to speculate about the *neural basis* of grapheme representation. Recent neuroimaging studies have found that in color-sensitive areas of ventral visual cortex, similar hues evoke similar patterns of activity (Brouwer & Heeger, 2009). Synesthetes show increased connectivity between color and grapheme areas (Rouw & Scholte, 2007). If the excess connectivity between these areas is systematic, then it is possible that similarly-encoded graphemes will elicit similarly-encoded colors (i.e., colors with similar hues) and visa versa. If true, this would imply that EFs influence inducer–concurrent relationships because EFs influence the underlying representational structure of the grapheme area of that synesthete's brain.

There are multiple grapheme-encoding areas in the brain, many of which are sensitive to particular grapheme properties, including visual features (Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002), phonological features (Rothlein & Rapp, 2014), and ordinal features (Fias, Lammertyn, Caessens, & Orban, 2007; Pariyadath, Plitt, Churchill, & Eagleman, 2012). One possibility is that there are different sets of potential inducer–concurrent relationships mediated by each grapheme area (i.e., "A" has a color associated with its ordinal position, its visual shape, etc.), and that reciprocal feedback between these areas causes the color associated with the most salient feature during development to crystallize.

Another possibility is that reciprocal feedback between many grapheme areas causes a single grapheme area to encode a non-linear "competitive" combination of these features; i.e., that the similarity structure of a single grapheme area aligns with the similarity structure of color space. A potential candidate for this is the grapheme area in fusiform gyrus described by Rothlein to be "amodal" (Rothlein & Rapp, 2014). Rothlein's claim that this area is amodal is derived from a series of tests in which the pairwise grapheme similarity matrix with fMRI response similarity as the distance metric is correlated with pairwise grapheme similarity matrices with other properties (such as acoustic or visual similarity) as distance metrics (Representational Similarity Analysis, see Kriegeskorte, Mur, & Bandettini, 2008). If this grapheme area were encoding a non-linear combination of features, this would not have shown up in Rothlein's statistical analysis. Our hypothesis makes a testable prediction in synesthetes: the pairwise grapheme similarity matrix of fMRI responses in this area should correlate more strongly with that synesthete's color distances than with any one property of the graphemes (visual, phonological, etc.).

Another important question our research leaves unanswered is how the relationship between ordinality and redness or distinctness is acquired. Very young synesthetes often experience a change in their specific grapheme-color associations across years, although their associations remain consistent across months (Simner & Bain, 2013). It is possible that this change in associations reflects learning of linguistic properties (e.g., letter frequency, pronunciation, etc.), and in the youngest children reflects the process of learning the language itself. Intriguingly, American children do not typically acquire their first graphemes in the order of the English alphabet (Justice, Pence, Bowles, & Wiggins, 2006), so it is possible that English-speaking synesthetes would not initially experience a red "A". Characterizing the development of this property of synesthesia (and others, such as the second order effects reported by Watson et al., 2012 and Asano & Yokosawa, 2013) could yield insights into how the brain acquires and organizes knowledge of graphemes.

It is interesting that the first grapheme is often distant and red. Another more broadly-applicable conclusion that can be drawn from our results is methodological: a multilingual synesthesia dataset is a powerful tool that can be used to generate testable predictions of theories that are confounded in monolingual datasets. We have chosen a particularly-salient example (the red "A"), but the etiology of many other associations remains unexplored. For example, is English "X" black because "x-rays" are black (Semantic EF; Mankin & Simner, 2017), or because sharp-shaped letters are black (Visual Shape EF; Spector & Maurer, 2011)? Or do these EFs combine additively to influence the color of "X" (i.e., "X" is *even more likely* to be black because of the congruent influences)? Although we found no evidence of an additive interaction for the red "A" (effect sizes were not always larger in languages in which EFs made congruent predictions), it is possible that such additive interactions exist in other graphemes. Future research should use multilingual synesthesia datasets to characterize the way in which EFs interact across all graphemes, not just for "A".

Some of the many reported properties of synesthesia may be universal, and some may be language-specific. If a property of synesthesia is shown to be language-specific, it is no less interesting. Indeed, if many properties of synesthesia turn out to be language-specific, then it might be possible to use synesthesia to study the representation of language more generally. For example, in Japanese-speaking synesthetes, similar sounding graphemes are similarly-colored, whereas English-speaking synesthetes' associations are not significantly correlated to phonetic similarity (Asano & Yokosawa, 2013). Asano and Yokosawa invoke the concept of orthographic transparency to explain this finding: in Japanese phonetic scripts (Hiragana and Katakana), the relationship between grapheme and phoneme is consistent, whereas English pronunciation is often idiosyncratic. If the amount of orthographic transparency predicts the influence of phonetic similarity on grapheme-color associations in other languages as well, this would be strong evidence that the properties of language can influence the phenomenology of synesthesia.

Future research should characterize the degree to which different letter properties (shape, sound, semantics, ordinality, etc.) contribute to synesthetic color for all letters across many languages. Systematic *similarities* across language in the degree to which a letter property influences a color property might yield insights into the etiology or neural mechanisms of synesthesia. Systematic *differences* across languages in the degree to which a letter property influences a color property might yield insights into how the properties of a language can influence letter representation in the brain. In this paper, we demonstrate that at least one property of synesthetic inducer–concurrent relationships appears to be universal: the first grapheme is often red, and is often distinct.

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Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.cortex.2017.12.003.

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