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What Language Tells Us About Synesthesia, What Synesthesia Tells Us About Language

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Experimental Psychology and Cognitive Science

by

Nicholas Bernard Root

Committee in Charge:

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Professor Sharon Rose
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2019

The Dissertation of Nicholas Bernard Root is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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Chapter 2, in full, is a preprint of material that has been submitted for publication. Root, Nicholas; Bhattacharyya, Pushpita; Ramachandran, V.S. The dissertation author was the primary investigator and author of this paper.

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ABSTRACT OF THE DISSERTATION

What Language Tells Us About Synesthesia,
What Synesthesia Tells Us About Language

by

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Doctor of Philosophy in Experimental Psychology and Cognitive Science

University of California San Diego, 2019

Professor V.S. Ramachandran, Chair

Grapheme-color synesthesia is a neurological phenomenon in which graphemes, such as letters of the alphabet, evoke an additional, automatic, consistent sensation of color (e.g. "R is sky blue"). An as-yet unsolved question in the field of synesthesia research is what causes a *particular* synesthete to associate a *particular* grapheme with a *particular* color. The present work explores how properties of synesthesia and properties of language interact during development to determine which color synesthetes (and even non-synesthetes) will associate with a particular grapheme.

Chapter One demonstrates that hypotheses about color etiology in synesthesia, which have long been confounded, can be disentangled using a multi-language dataset: language can help us understand synesthesia. Chapter Two describes a case study of a Bengali grapheme-color synesthete, the first ever report of synesthetic phenomenology in an abugida writing system. Systematic differences between synesthesia in Bengali and in English suggest ways in which Bengali grapheme representations might be structured: synesthesia can help us understand language. Chapter Three demonstrates that synesthesia research can generalize to the (much larger) non-synesthetic population by engaging with a long-standing debate about the whether synesthesia is "special" or on one end of a continuum of experience. Non-synesthetes are found to have "synesthesia-like" associations for a subset of letters, suggesting that differences between synesthetes and non-synesthetes are differences in degree, not in kind. Chapter Four probes the limits of this generalizability, demonstrating that synesthetic and non-synesthetic associations are sometimes different because synesthetes' associations are "locked in" during childhood, whereas non-synesthetes' associations remain flexible through adulthood. Together, these studies suggest that synesthesia offers a window into the brain, that lets us literally *see* how we think about letters.

GENERAL INTRODUCTION

Grapheme-color synesthesia is a neurological phenomenon in which viewing a grapheme (contrastive units in a language such as letters, Japanese kana, or Chinese ideographs) elicits an additional, automatic, consistent sensation of color. When describing their experiences, synesthetes often use very precise language (e.g., "R is sky blue."), and will consistently pick the same color on a computerized color-picker when asked to match graphemes to their colors, even when they are re-tested after months or years (Asher, Aitken, Farooqi, Kurmani, & Baron-Cohen, 2006). There is converging evidence from behavioral (e.g. Ramachandran & Hubbard, 2001), electrophysiological (Brang, Edwards, Ramachandran, & Coulson, 2008), and fMRI (Nunn et al., 2002) studies that synesthesia is a genuine perceptual experience: synesthetes *actually see* the colors (Palmeri, Blake, Marois, Flanery, & Whetsell, 2002).

The relationship between a grapheme and its color was once thought to be idiosyncratic: two synesthetes often experience the same grapheme as colored differently. Modern research using large number of subjects has dispelled this misconception: synesthetes tend to associate certain graphemes with certain colors (Simner et al., 2005). Many of these biases can be attributed to properties of language. So, what can language tell us about synesthesia? What can synesthesia tell us about language? In the present work, I show how exploring these questions can assist us in the pursuit of one of the "end-goals" of synesthesia research: explaining why a *particular* synesthete experiences a *particular* grapheme as a *particular* color.

What can language tell us about synesthesia?

What causes synesthetes to experience colors for graphemes? One prominent hypothesis about the etiology of grapheme-color synesthesia is the "cross-activation theory": color experiences could be caused by excess connectivity between the color area V4 and the grapheme area VWFA, which are anatomically close in fusiform gyrus (Rouw & Scholte, 2007). The cross-activation theory explains why synesthetes experience graphemes as having a color, but they do not explain why synesthetes experience a *particular* grapheme as having a *particular* color.

One productive route to answering this question has been to study grapheme-color synesthesia from a psycholinguistic perspective (Simner, 2007): linguistic properties such as pronunciation, semantics, and letter frequency have been shown to act as *Regulatory Factors* (RFs), influencing the specific color(s) likely to be associated with specific graphemes. For example, semantic associations such as color names can exert strong influence on synesthetic associations: “R” is often red, “Y” is often yellow, “G” is often green, and so on (Simner et al., 2005). Linguistic properties can even influence the *relationship between associations*; for example, similarly-shaped letters tend to be associated with similar colors (Brang, Rouw, Ramachandran, & Coulson, 2011).

Together, these results suggest that the specific grapheme-color relationships experienced by synesthetes are not random, but instead might reflect underlying properties about the synesthete’s language. However, the manner in which Regulatory Factors interact to determine synesthetic color is an open question, and the contributions of different RFs to a grapheme-color association are often confounded. For example, it is commonly reported that English-speaking synesthetes experience a red “A” (Simner et al., 2005, Root et al., 2018). Various researchers have proposed that this association is caused by different RFs, including sound (Asano & Yokosawa, 2013), shape (Brang, Rouw, Ramachandran, & Coulson, 2011), semantic associations (Mankin & Simner, 2017), and ordinality (Rouw, Case, Gosavi, & Ramachandran, 2014). How can we determine which RF(s) are responsible for this association, when each RF makes the same prediction ("A" should be red)?

Multi-language datasets can help adjudicate between competing hypotheses about synesthetic etiology. Consider the confounded explanations for the red "A": the RFs are confounded *in English*, but in a multilingual dataset they make different predictions. Despite more than a decade of research into psycholinguistic aspects of synesthesia, only a few studies have reported data from non-English-speaking synesthetes, and *no published study* (other than those in the present work) has ever compared data from synesthetes with different native languages. **Chapter 1** is the first ever study of synesthesia using data from multiple native languages; it uses this novel dataset to confirm that "A" is red because it is the first letter of the alphabet, and that this RF ("The first grapheme is typically red.") appears to be universal.

What can synesthesia tell us about language?

In Chapter 1, we explored a property of grapheme-color synesthesia that is potentially "universal" - the first letter of the alphabet is red in every language we have thus far measured. Are there also examples of *language-specific* synesthetic phenomenology that depends on the properties of the language in which it is experienced? One piece of evidence in support of this idea comes from studies of *orthographic depth*: languages vary in the consistency with which a particular grapheme is mapped onto a particular phoneme; for example, English is very orthographically "deep", whereas Japanese is very orthographically "transparent". Asano and Yokosawa (2013) propose that Regulatory Factors exert different amounts of influence in different languages, depending on how much that RF can help us distinguish between different graphemes. Consistent with this hypothesis, grapheme-color associations in English are not influenced by pronunciation (Watson, Akins, & Enns, 2012), whereas in Japanese synesthetes, similarly-pronounced letters are associated with similar colors (Asano & Yokosawa, 2013). By comparing the effect of RFs between languages, we can gain insights into differences in language representation. More generally, synesthesia does not look the same in every language.

How different can synesthesia look from the typical experience of American English-speaking synesthetes? In **Chapter 2**, we describe a case study of a Bengali grapheme-color synesthete. Bengali is written using an *abugida*, a segmental writing system in which consonants are modified with vowel diacritics; Bengali also has several unique linguistic features, such as "conjunct consonants", in which two consonants are written using a single grapheme that resembles (but is not identical to) the shapes of its constituents' graphemes. Our study is the first report in the literature of synesthesia in an abugida, and across several experiments we demonstrate just how different synesthetic phenomenology can be in a non-alphabetic language. Our results suggest that studying synesthesia cross-linguistically yields clues about how the brain's representation of graphemes can depend on properties of the language.

Why should we care about grapheme-color synesthesia?

In two chapters of this work, we give two small illustrations of how findings from synesthesia research can inform our understanding of non-synesthetes in the general population.

Chapter 3 is a short response to a fundamental debate in the synesthesia research field: are synesthetes "special", or are they at one end of a continuum of experience? We show that for a small subset of their letters, English-speaking non-synesthetes look very much like synesthetes: they experience "synesthesia-like" color associations that are consistent over time, and express confidence that their color choice for these associations is the "best" one. We conclude that although there are clearly *some* differences between synesthetes and non-synesthetes, patterns of grapheme-color associations are highly similar across these groups, and thus findings in synesthetes (e.g. from Experiments 1 and 2) are likely to generalize to non-synesthetes.

Chapter 4 starts where Chapter 3 ends: synesthetes and non-synesthetes share many, *but not all*, patterns of grapheme-color association. What then explains the *differences* between the associations of synesthetes and non-synesthetes? We demonstrate that one source of these differences is the developmental trajectory of grapheme-color associations: synesthetic children begin to "lock in" their associations by ages 6/7 (Simner, Harrold, Creed, Monro, & Foulkes, 2008), whereas non-synesthetes' associations remain flexible in adulthood. We trace a particular association that is unique to synesthetes in adulthood (female synesthetes associate their first initial with the color pink; female non-synesthetes do not) to childhood gender-color stereotypes. Specifically, we show that in girls between ages 5-7, even non-synesthetes associate their first initial with the color pink. This association disappears in adult non-synesthetes (who instead associate their first initial with their current favorite color), but remains "locked in" in synesthetes. We suggest that grapheme-color associations unique to synesthetes are a "time capsule" into associations experienced by children during development.

In sum, we demonstrate that cross-language datasets are a valuable tool in the synesthesia researcher's quest to explain the etiology of grapheme-color associations, that synesthesia is a valuable tool in the psycholinguist's quest to explain grapheme representation, that studies of grapheme-color association in synesthetes will likely generalize to non-synesthetes, and that differences between synesthetes and non-synesthetes can offer clues about the trajectory of language learning during childhood.

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CHAPTER 1

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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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

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[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.

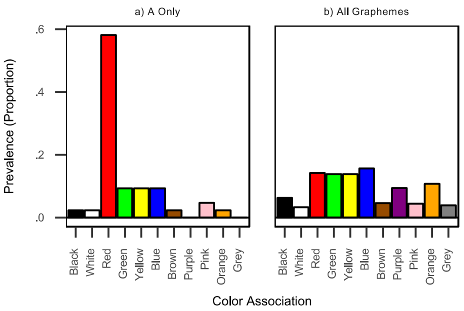

Fig. 1 – Proportion of associations in each color category for “A” (a) or all graphemes (b).

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 $O_i|_{1 \le i \le k}$, 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).

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

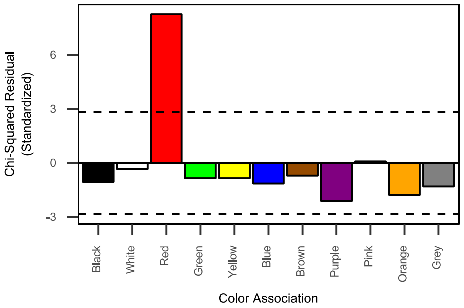

Fig. 2 – The standardized residuals of a chi-squared goodness of fit test of the hypothesis that the observed associations for “A” (Fig. 1a) come from the overall distribution of colors (Fig. 1b). The dotted line depicts the $p < .0045$ threshold for significance (alpha level adjusted from .05 using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

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[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.

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 /a:/ (in IPA), as hypothesized by Marks (1975), then the letter that encodes the phoneme /a:/ 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.

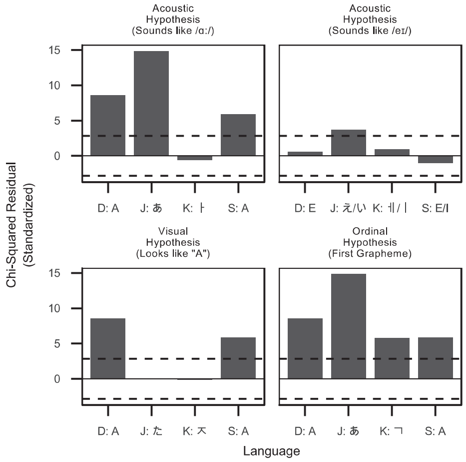

Fig. 3 – The standardized Pearson residuals for the red residual of a chi-squared test of the distribution of colors for the grapheme that each Exploratory Factor (Acoustic, Visual, Ordinal) predicts should be red. The dotted line depicts the $p < .0045$ threshold for significance (alpha level adjusted 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.

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.

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 (/aː/)	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

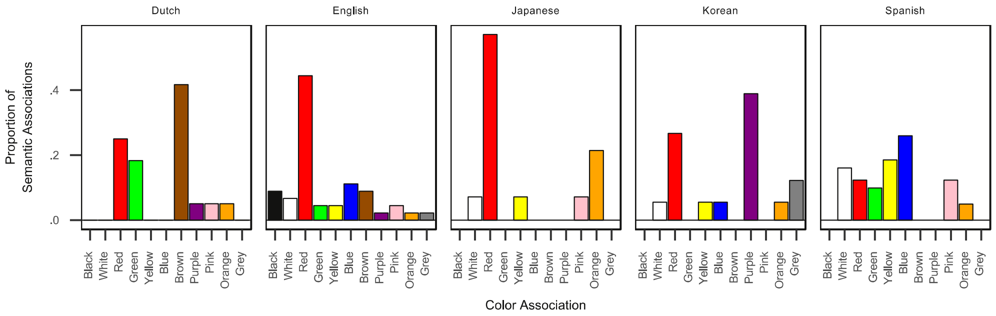

Fig. 4 – The normalized proportion of color responses for the index words in each language. These proportions correspond to the null hypothesis that all inducer–concurrent relationships are explained by the Semantic EF.

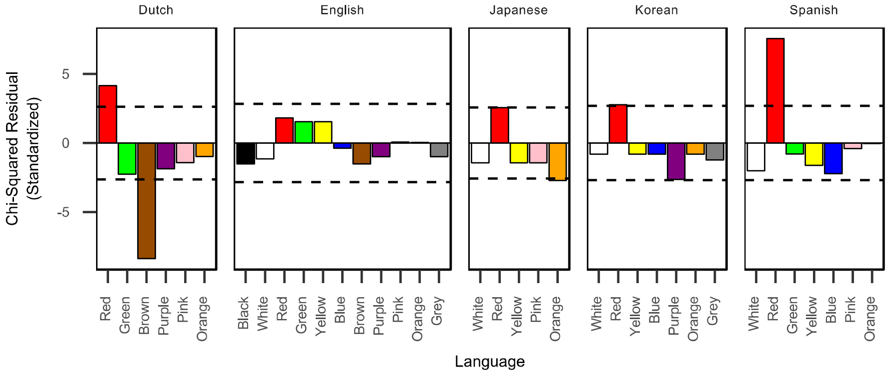

Fig. 5 – The standardized residuals of a chi-squared goodness of fit test of the hypothesis that the observed associations for the first grapheme come from the distribution of associations predicted by the Semantic EF. The dotted line depicts the Bonferroni-corrected significance threshold for an alpha 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-

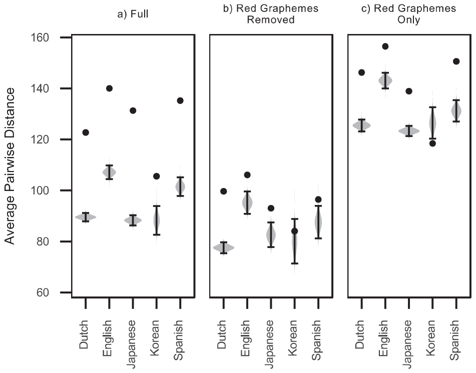

Fig. 6 – Results of Monte Carlo permutation tests (N = 100,000), with the null hypothesis that grapheme labels are exchangeable within-subject. The black dot depicts, for each language, the average pairwise Euclidean distance between the first grapheme and other graphemes in the uv plane of CIELuv space. 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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CHAPTER 2

Grapheme-Color Synesthesia in an Abugida: A Bengali Case Study

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ABSTRACT

Grapheme-color synesthetes experience graphemes (e.g. letters of the alphabet) as having a consistent color. Most studies of grapheme-color synesthesia have only examined synesthetes in English, leaving underexplored the question of how synesthetic phenomenology might differ in languages that do not use alphabets. In particular, grapheme-color synesthesia in an *abugida* (a segmental writing system in which consonant graphemes are modified with vowel diacritics) has never been studied. Here, we present a case study of a Bengali synesthete, MJ, the first report of a grapheme-color synesthete in an abugida. First, we show that for MJ, diacritics influence the overall color of the consonant grapheme they modify, "pulling" it towards the color she experiences for the vowel. Second, we present a descriptive analysis of the complex synesthetic experiences reported by MJ for conjunct consonants, a unique orthographic feature of Brahmi-derived scripts such as Bengali. Finally, we show that despite these language-specific features, MJ's synesthetic associations are influenced by linguistic properties (such as orthographic and phonetic similarity) in the same manner as synesthetic associations in other languages. We conclude that the idiosyncratic features of MJ's synesthesia reflect unique properties of the Bengali writing system, and suggest that more cross-language studies of synesthesia are needed.

INTRODUCTION

Most people who read this text will experience it as written in black ink, but for *grapheme-color synesthetes*, each letter evokes a consistent sensation of color. For example, a synesthete might say that "The letter 'R' is always sky blue". The letter-to-color associations of synesthetes are consistent across years of testing (e.g., if "R" is sky blue now, it will be the same sky blue a year from now; Asher, Aitken, Farooqi, Kurmani, & Baron-Cohen, 2006). Grapheme-color synesthesia is thought to be caused by excess connectivity between brain regions (e.g., between color and letter-form areas in the fusiform; Rouw & Scholte, 2007), and gene linkage studies suggest that the propensity to develop synesthesia is at least partly genetic in origin (Tilot et al., 2018), but the consistency of grapheme-color associations presents a challenge to purely "genetic" models: although it seems plausible that genetic differences could cause synesthetes to experience colors with letters, it seems implausible that genetic differences could determine *which* color is associated with *which* letter - after all, we are not born with knowledge of letters.

The specific grapheme-to-color associations of synesthetes were long thought to be idiosyncratic (Deroy & Spence, 2013), but recent studies using large samples of synesthetes find many environmental correlates of synesthetic associations. Perhaps the most direct causal "story" of the etiology of specific associations comes from Witthoft & Winawer (2006), who found some synesthetes whose synesthetic associations could be reliably attributed to the colors of Fisher-Price refrigerator magnets[1]. "Fisher-Price"-like associations explain the grapheme-to-color pairings of only a small subset of synesthetes (in particular, those who were born in the 1970s, when the Fisher-Price refrigerator magnet set was released; Witthoft, Winawer, & Eagleman, 2015), but they powerfully illustrate the idea that regularities in the environment can shape *which* grapheme tends to be associated with *which* color. Indeed, numerous such "Regulatory Factors" have now been described: for example, letter shape (Brang, Rouw, Ramachandran, & Coulson, 2011), pronunciation (Asano & Yokosawa, 2011; Kang, Kim, Shin, & Kim, 2017), semantics (Mankin & Simner, 2017), and letter frequency (Watson, Akins, &

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[1] Note that it is the *specific associations* that seem caused by the refrigerator magnets, not the synesthesia itself. For those already predisposed to become synesthetes, refrigerator magnets shaped the pattern of their grapheme-color associations; there is no evidence that the magnets *caused* synesthesia. (Witthoft & Winawer, 2006)

Enns, 2012) have all been shown to influence which color synesthetes tend to associate with which grapheme.

Grapheme-color synesthesia in non-alphabetic writing systems

Many factors that influence synesthetic associations are linguistic in origin, suggesting that grapheme-color synesthesia should be considered a psycholinguistic phenomenon (Simner, 2007). Although numerous studies have examined linguistic influences on synesthesia, there has been surprisingly little research on synesthesia in languages other than English. The possibility that synesthesia could differ between speakers of different languages was first proposed by Eduard Gruber at the first known synesthesia conference (the 1889 International Symposium on Synesthesia in Paris), but he never published his work (Jewanski, Simner, Day, Rothen, & Ward, 2019). In the years since, hundreds of papers on synesthesia have been published, but fewer than 15 have examined subjects in a non-Latin alphabet, and to our knowledge only one (the first chapter of this dissertation) has explicitly *contrasted* the synesthetic experience of synesthetes with different native languages (Root et al., 2018).

Of particular interest are studies examining synesthesia in languages that use writing systems other than alphabets. Alphabetic writing (in which graphemes represent phonemes) is only one of several types of writing system (Daniels & Bright, 1996): graphemes in *syllabaries* each represent syllables, graphemes in a *logographic* system each represent words or morphemes, graphemes in *abugidas* represent consonant-vowel combinations using a consonant grapheme base and secondary vowel notation (e.g. diacritical markers), and graphemes in *abjads* represent consonant-vowel combinations using a consonant grapheme only (readers must infer the appropriate vowel based on cues such as grammatical rules). Critically, different writing systems can be processed differently in the brain (Nag, Caravolas, & Snowling, 2011): reading in alphabetic languages classically activates left fusiform gyrus (McCandliss, Cohen, & Dehaene, 2003), whereas reading in Chinese involves additional activation in the right hemisphere (Tan et al., 2001), and reading of Devanagari (an abugida) and Japanese (a syllabary) involves additional activation in right superior parietal lobe (Das, Kumar, Bapi, Padakannaya, & Singh, 2009). Systematic cross-language variation in synesthetic phenomenology that can be attributed to writing system might thus offer valuable clues about the nature of reading processes in these languages.

Only a few studies have examined synesthesia in non-alphabetic writing systems. On the one hand, these findings demonstrate distinctly-different phenomenology of synesthesia in other writing systems. Taken collectively, however, these studies show that the influence of psycholinguistic factors on synesthetic associations extends to writing systems other than alphabets.

Simner, Hung, & Shillcock (2011) compared synesthetic phenomenology in native (L1) and second-language (L2) Chinese speakers; of particular interest, they measured synesthetic associations in both Hanzi Chinese characters (the Chinese logography) and in Pinyin (i.e., the Romanized version of the characters, taught alongside Chinese characters in elementary school and in language classes). They found that while L2 speakers of Chinese associated Chinese characters and their Pinyin equivalents with the same color, L1 speakers often had different colors for the representation in each writing system; Simner et al. suggest that L1 speakers associate colors to graphemes via different mechanisms for the two writing systems. In a follow-up study, Hung, Simner, Shillcock, & Eagleman (2014) examined the associations of L1 Chinese speakers in greater detail, and found that the synesthetic colors of Chinese characters are influenced by its component radicals (morphological units), and that the radicals' colors were influenced both by their function (semantic vs. phonetic) and position (left vs. right). Hamada, Yamamoto, and Saiki (2017) examined Japanese speakers' grapheme-color associations for Kanji (Chinese characters borrowed for Japanese), and illustrated a limitation of previous studies of synesthesia in logographies: in Hamada et al.'s experiment, synesthetes were allowed to choose more than one color, and often did so; in follow-up interviews, these synesthetes indicated that each radical could be associated with a different color (rather than the compound character being associated with a single color). Hamada et al.'s synesthetes experienced two or more colors for more than half of the tested Kanji; this result differs markedly from synesthetic phenomenology in English, in which we know of only one case report of a letter experienced as multicolored (Hubbard & Ramachandran, 2005).

The only syllabary in which synesthesia has been studied is Japanese Hiragana; Asano & Yokosawa (2013) found that synesthetic colors for Hiragana graphemes were influenced by grapheme ordinality and visual shape (like in the alphabetic English), but also by pronunciation (in contrast to English, in which sound does not influence synesthetic associations; Watson et al., 2012). Furthermore, color associations for Kanji (the Japanese logography, which uses Chinese characters) were strongly correlated with the color associations of their phonetic spelling in Hiragana (Asano & Yokosawa, 2012). This is consistent with Mankin et al.'s description of L2 Chinese learners, suggesting that the cross-script consistency may be a function of late script learning (Japanese students typically learn Kanji later than Hiragana, while Chinese students begin to learn Chinese characters before they learn Pinyin; Shu, Peng, & McBride-Chang, 2008) rather than a function of native vs. non-native language.

Only one paper has examined synesthesia in an abjad: Van Leeuwen, Dingemanse, Todil, Agemeya, & Majid (2015) found that grapheme-color associations in Arabic were driven by language-specific psycholinguistic features such as frequency of a grapheme's occurrence in the language, intrinsic ordering of graphemes and the unique feature of the 'root' in the word formation process in Arabic, while grapheme shape and sound appeared to have a negligible influence on color associations, despite their established importance in other language systems.

Finally, to our knowledge no published work has described synesthesia in an abugida (quite astonishing, given that there are nearly as many Hindi speakers in the world as English speakers…). Here, we present a case study of synesthete MJ, the first description of synesthesia in an abugida.

Synesthete MJ

MJ is a left-handed 23-year-old female international student at UCSD. She was born in the United Kingdom to an Indian Bengali family, where she was exposed to Bengali at home and English in daycare and preschool. At age 3, she moved with her family to Kolkata, India, where family, friends, neighbors, etc. spoke Bengali, while her instruction in school was primarily in English (an "English-medium" school). MJ considers herself a balanced bilingual; although she learned to write in Bengali later (age 6) than the English alphabet (age 3), she had native levels of fluency in both languages by age 4. When asked which languages she currently "thinks in", she reports that as a US resident she currently thinks primarily in English, but that when she communicates with a Bengali speaker, she switches to thinking in Bengali.

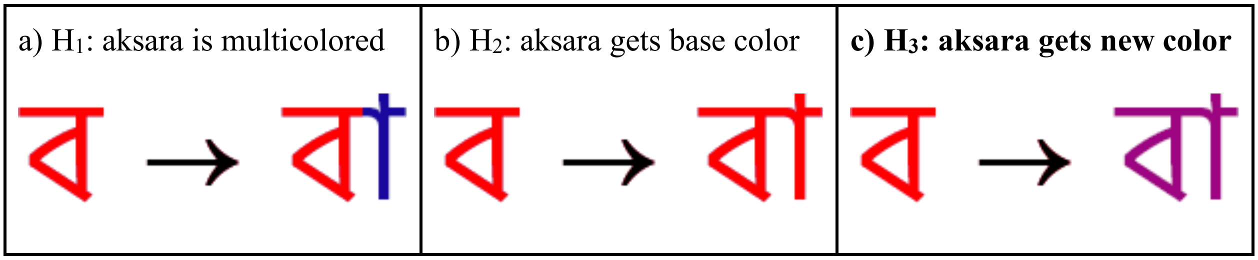
When we interviewed MJ, we first asked her to describe her synesthetic experiences. She reports having experienced synesthesia since childhood, including grapheme-color, month-color, day-color, and sound-color. She had previously taken the Eagleman Synesthesia Battery (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) for English grapheme-color, musical instrument-color, month-color, and day color, and she has exceptionally high test-retest consistency on all tests (well surpassing the threshold for synesthesia; Rothen et al., 2013). Her description of her synesthesia is more consistent with associator-type than projector-type synesthesia, and her Eagleman Battery Projector/Associator score indicates that she is an associator synesthete. In the present work, we describe a number of experiments we conduct on MJ's grapheme-color synesthesia in the Bengali abugida, asking how her experiences are shaped by the unique features of Bengali and of abugidas more generally. In Experiments 1 and 2, we explore *differences* in synesthetic phenomenology for abugidas, examining the influence of grapheme features that are unique to abugidas; in Experiment 3 we explore *similarities* in synesthetic phenomenology for abugidas, asking whether MJ's Bengali associations are driven by some of the same influences reported for other languages.

EXPERIMENT 1: DO DIACRITICS INFLUENCE GRAPHEME COLOR?

The Bengali writing system is an *abugida*, in which consonant-vowel (CV) pairs are represented by a consonant grapheme and a vowel diacritical mark. For example, in Bengali, "সুখ", pronounced /ʃuk^{h}/, the /u/ is denoted by the diacritic "◌ু" underneath the /ʃ/ consonant base, "স". Vowels are represented as "independent" graphemes rather than diacritical marks only when they are in word-initial position (e.g. in "আম", pronounced /am/, "আ" is the vowel /a/), or when they come directly after another vowel (e.g. in "হাওয়া", pronounced /haowa/, /a/ is denoted by the diacritic "◌া" on the consonants "হ" and "য়", but /o/ is represented as the vowel grapheme

"ও"). Since consonant graphemes are always associated with a vowel, additional "conjunct" graphemes are used to represent consonant clusters (Sircar & Nag, 2013). Typically, conjunct graphemes are written by visually merging two or more consonants (e.g. in the Bengali word "ছন্দ", pronounced /tʃʰɔ**nd**ɔ/, the /nd/ cluster is written by combining the /n/ and /d/ consonants, "ন" + "দ" = "ন্দ"; similarly, "স" + "ট" = "স্ট"; "শ" + "ব" = "শ্ব"). However, some consonant clusters are represented by conjunct graphemes containing visual features that do not resemble the graphemes for their constituent consonants (e.g. in "রক্ত" pronounced /rɔ**kt**ɔ/, "ক (k)" + "ত (t)" = "ক্ত"); similarly, "ষ" + "ট" = "ষ্ট"; "ঞ" + "জ" = "ঞ্জ"). The basic unit of Bengali writing is called an 'aksara', which roughly corresponds to the onset+nucleus portion of a syllable, and consists of either a base consonant or conjunct consonant plus its inherent vowel (without diacritic; e.g. "স"), a base consonant or conjunct consonant plus an attached diacritic vowel (e.g. "সু"), or an independent vowel grapheme (e.g. "আ") (Bright, 2000).

We wondered how synesthesia might differ in such a writing system. In particular, we wondered how diacritical marks might contribute to synesthetic phenomenology. There are at least three possibilities. **First**, aksara could have multiple colors - one for the consonant base, one for the diacritical mark (e.g. Figure 1a). This possibility would be consistent with the experience of Japanese synesthetes' experience of radicals in the logographic Kanji orthography: radicals and the base characters they modify are sometimes associated with different consistent colors (Hamada et. al, 2017). **Second**, aksara could remain the same color as the consonant base regardless of diacritic; i.e., the diacritic could have no effect on the color (e.g. Figure 1b). This possibility would be consistent with the effect of vowels in Korean, which do not modify the initial consonant in CV pairs (Shin & Kim, 2014). **Third**, aksara could be associated with a single color that is different from the color of the consonant base; i.e. the diacritic could influence the color of the consonant base in some way (e.g. Figure 1c).


a) H_1: aksara is multicolored

b) H_2: aksara gets base color

c) H_3: aksara gets new color

Figure 2.1: three hypothetical patterns of grapheme-color associations for the aksara “বা”, which is composed of the consonant base “ব” plus the diacritic “◌া”. a) the aksara is multicolored, with the base and diacritic each colored separate; b) the consonant base does not change color when diacritics are added. c) the entire aksara changes color when diacritics are added. MJ’s subjective descriptions are most consistent with the hypothesis in (c): diacritics change the color of the entire aksara.

When we asked MJ to subjectively describe the colors for various aksara, we quickly eliminated the first possibility: she described aksara as having a single color. When we asked her to compare the color for pairs of aksara with the same consonant base but different diacritics, she indicated that the color of the aksara changed depending on the diacritical mark. However, synesthetes’ associations (including MJ) are not *perfectly* consistent over time (e.g. average distance across 3 trials; Rothen, Seth, Witzel, & Ward, 2013), and are sensitive to viewing conditions such as whether the grapheme is in central vision vs. the periphery (Brang & Ramachandran, 2010), or even whether the letter is viewed in high-contrast vs. low-contrast background; Hubbard, Manohar, & Ramachandran, 2006). In other words, MJ’s report that diacritics influence aksara color could reflect random variation or viewing confounds rather than a true effect of diacritic on the grapheme color. Therefore, we sought to verify that MJ’s subjective impressions were accurate, and to quantify the effect of vowel diacritic (if any) on aksara color.

Methods

To verify our observations, we designed an online color picker that was functionally identical to the Eagleman Synesthesia Battery (Eagleman et al., 2007) and collected grapheme-color associations from MJ for different aksara. For the consonant base, we chose four consonant bases (“গ”, “প”, “ব”, “স”) for which MJ experienced distinct colors (green, red, blue, and yellow, respectively). For each consonant, we generated aksara for the ten possible CV pairs (consonant with implied vowel, plus the 9 Bengali vowel/diphthong diacritics). We also included the independent graphemes for the 10 Bengali vowels/diphthongs. In sum, we measured MJ’s grapheme-color associations for a total of 50 aksara. Each grapheme was presented in random order, and then this process was repeated 3 times, for a total of 150 trials. On each trial, MJ used an RGB color picker to choose the color she experienced for the presented aksara. Colors were then converted to the CIELuv color space, the perceptually-uniform color space typically used in synesthesia research (Rothen et al., 2013).

Results and Discussion

Do diacritical marks change the color of the grapheme?

Figure 2a depicts an example of the distribution of color choices in the uv plane for the “ব” consonant. Qualitatively, color associations across 3 repetitions of a base-diacritic grapheme do seem to cluster slightly, suggesting that diacritical marks might change the color of the grapheme in a consistent way. To quantify this observation, we computed the average distance in CIELuv color space between the three repeated trials for each CV grapheme, and then computed the distance obtained when randomly shuffling the diacritic label (i.e., a permutation test). The average pairwise distance between repeated measures of the same aksara was 21.9. To compare this distance to the distance expected by chance, we used Monte Carlo resampling (10000 replications) to repeatedly calculate the average pairwise distance when diacritic label was randomly scrambled. The test-retest difference for each askara was indeed smaller than would be expected by chance (Figure 2c; permutation test, 10000 replications, $distance_{expected} = 33.16$, $distance_{observed} = 21.9$, H_0 95% CI: $[28.99, 36.63]$, $p < 0.001$). Thus, for MJ, diacritics influence the color of the grapheme in a consistent way.

Is the effect of diacritic on color consistent across consonants?

We have shown that effect of diacritics on aksara color is *consistent*, but we have not yet shown whether the effect is *systematic*. For example, the color for /pɔ/ is distinct from the color for /pi/, and the color for /kɔ/ is distinct from the color for /ki/, but does the /i/ influence both consonants *in the same way*? We hypothesized that the color of an askara might be the color of its base consonant “pulled” towards the color of its diacritic’s vowel grapheme. Figure 2b depicts the average associations for each of the aksara for the “ব” consonant (the averages of the “triangles” in Figure 2a), with two arrows: one from the base consonant to the aksara, and one pointing from the aksara towards the location of its diacritic’s vowel grapheme (when the vowel is in initial position). We qualitatively noted that each pair of arrows generally points in the same direction, suggesting that the vowel graphemes associated with each diacritic might indeed “pull” the color of the consonant base towards them.

To quantify this observation, we first computed the average in CIELuv space across the three test-retest repeats, yielding a single color in CIELuv for each aksara. For each aksara (e.g. বু; /bu/), we calculated the distance in CIELuv between the aksara and its diacritic’s vowel grapheme (বু /bu/ -> উ /u/), and the distance in CIELuv between the aksara’s base consonant and the same vowel grapheme (ব /bɔ/ -> উ /u/). Our hypothesis was that on average, the distance between the color of an aksara and the color of its associated vowel (বু /bu/ -> উ /u/) was smaller than the distance between the color of its consonant base and the color of the vowel (ব /bɔ/ -> উ /u/), i.e., the vowel "pulled" the color. Indeed, aksara were on average 10 units closer to their vowel than were the aksara's consonant bases. To find out how likely it is that this would happen by chance, we constructed a null hypothesis distribution of the same statistic using Monte Carlo resampling with 10000 repetitions: we randomly shuffled the diacritic label for each aksara, and for each repetition calculated the "pull"; we then compared this sampling distribution to the actual "pull" that we observed. Indeed, on average the aksara was pulled towards its vowel significantly more than would be expected by chance (Figure 2d; permutation test, 10000 replications, $pull_{expected} = 3.20$, $pull_{observed} = 10.0$, H_0 95% CI: $[-0.79, 8.24]$, $p < 0.001$). In other words, for MJ, diacritics "pull" the color of an aksara away from the base consonant and towards the color of the diacritic's vowel grapheme.

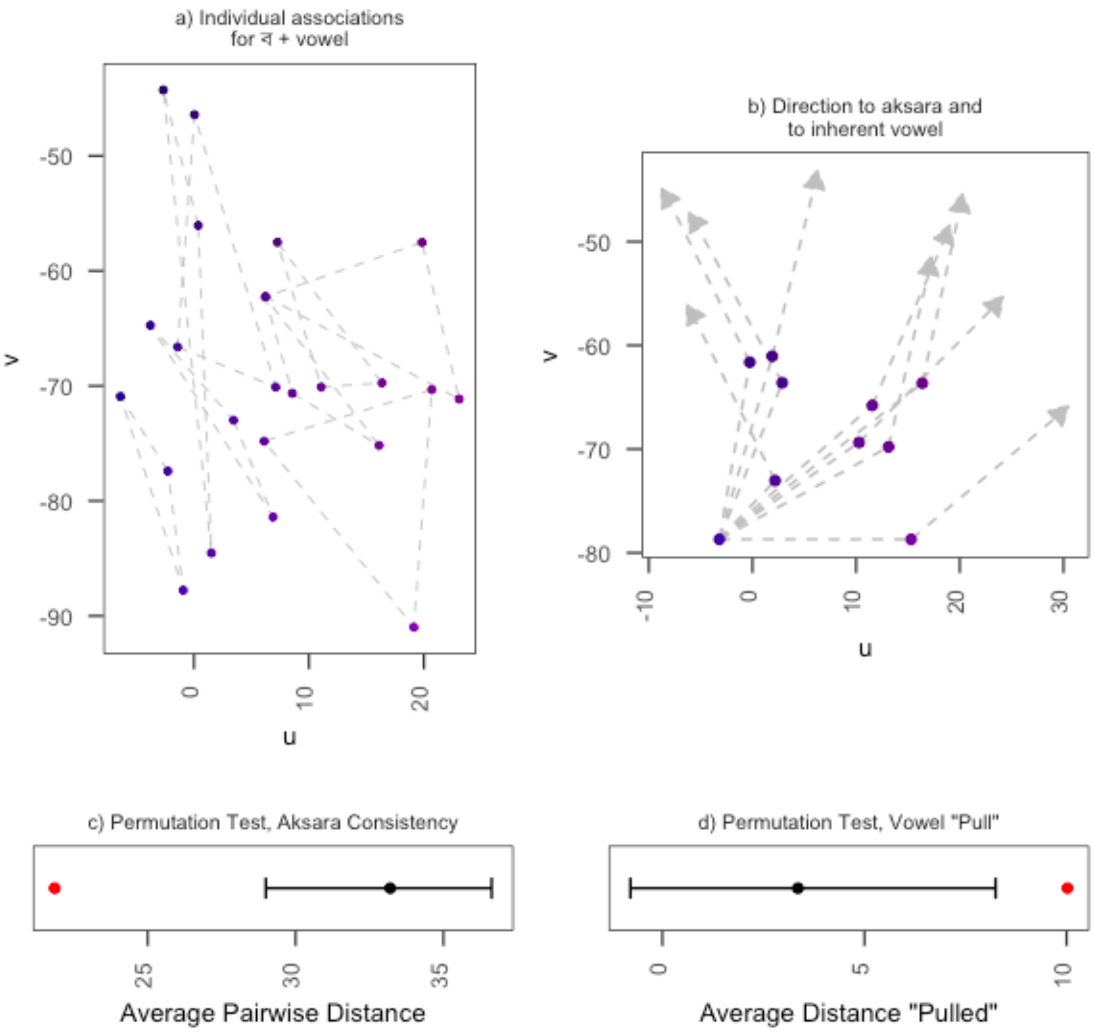


Figure 2.2: Visualizations of consonant-diacritic aksara and their colors. a) Individual trial-level associations for the "ব" consonant plus each vowel. Dotted lines connect the 3 repetitions of each trial; our question is whether points connected by triangles are closer to each other than they would be if randomly-selected points were connected. b) Direction vectors from "ব" (consonant + inherent vowel /ba/) to each of its nine associated aksara (consonant + vowel diacritic), plus direction vectors from each aksara towards the color for the vowel grapheme of the aksara's vowel diacritic. The two arrows generally point in the same direction, suggesting that each vowel grapheme is "pulling" the aksara towards it. c) The distribution of average pairwise test-retest distance expected if diacritics do not influence aksara (Monte Carlo resampling, diacritics shuffled, 10000 repetitions). The red point indicates the observed pairwise test-retest distance. d) The distribution of average "pull" expected if independent vowel graphemes do not influence the color of aksara (Monte Carlo resampling, diacritics shuffled, 10000 repetitions). The red point indicates the observed "pull" from vowel graphemes.

EXPERIMENT 2: BENGALI CONJUNCT CONSONANTS

Conjunct consonants in Bengali represent an interesting test-case for theories of synesthetic associations. Grapheme-color associations are nearly always between a grapheme and a *single* color, but in the languages described in the synesthesia literature, there are typically not meaningful subdivisions of graphemes (after all, graphemes are the “smallest meaningful contrastive unit” of a language; Coulmas, 1996). Conjunct consonants arguably have sub-graphemic features: as described above, Bengali conjunct consonants are often typographic ligatures (Sircar & Nag, 2013), in which visual features of the component consonant graphemes are “fused” together into a single conjunct grapheme. This leaves open the possibility that conjunct graphemes might be associated with multiple colors.

More generally, we imagined three possibilities for MJ’s conjunct-color associations. **First**, the conjunct could be associated with a single one of the colors of the component consonants (either the first or the second consonant). **Second**, the conjunct could be associated with a single color that is not related to either of the component consonants’ colors. **Third**, the conjunct could be associated with both of the colors of the component consonants, such that the visual features associated with each consonant keep their original colors. In a qualitative interview, when presented with various Bengali conjunct consonant characters, it was clear that MJ experienced a mix of all three types of association: some of her conjuncts were a single color, whereas others were multicolored; some of her conjuncts were clearly derived from the component consonant colors, whereas others were uniquely-colored. In this experiment, we will qualitatively describe the various experiences MJ reports for her conjunct consonants.

Methods

To better characterize MJ's observations about her conjuncts, we measured her associations for 20 conjunct consonants using a multi-step procedure (there are hundreds of conjuncts, so it would be impractical to measure the association for every conjunct; we tried to choose conjuncts with subjectively-interesting properties - one that was a conjunct of two of the same consonant, one that was visually distinct from its component conjuncts, etc.). First, we presented each conjunct consonant and asked MJ to indicate whether she experienced one *vs.* two (or more) colors. If she indicated that she associated a conjunct with a single color, we measured her color association using the same online color picker as in Experiment 1. If she indicated that she associated a conjunct with more than one color, we asked her to use Photoshop to draw the conjuncts as she experienced them. In both cases, we tested MJ on the same conjuncts three times each, enabling us to assess test-retest consistency. In addition, we collected color associations for the base consonants for all conjuncts, using the same online color picker as in Experiment 1.

Results and Discussion

MJ indicated that for 11/20 of the conjuncts we tested, she experienced a single color, and for the remaining nine she experienced two colors.

Single-color conjuncts.

We first verified that MJ's colors for conjuncts were consistent over time, by quantifying the test-retest consistency using the methods from Rothen et al. (2013). We calculated consistency as the average of the sum Euclidean pairwise distance between repeated trials; MJ's average consistency was 59.1, well below the commonly-used threshold for synesthesia, 135 (Rothen et al., 2013). Having established the consistency of MJ’s conjunct associations, we took the average in CIELuv color space across three trials, yielding a single color for each conjunct.

We next examined MJ’s single-color conjunct associations and compared them to her associations for each component consonant. Table 1 depicts these associations, arranged by a subjective potential derivation. Two conjuncts were double consonants encoded by repeating the base consonant (e.g. “চ্চ” is two“চ” put together); for these two conjuncts MJ’s associations were clearly indistinguishable from the color of the base consonant. Two conjuncts seemed to be colored similarly (but not identically) to the first base consonant. Two conjuncts seemed to be colored similarly (but not identically) to the second base consonant. Three consonants seemed to be a mix of the first and second base consonant’s color. Finally, for two consonants there was no clear relationship between the color of the base consonants and the conjunct color.

Table 2.1: MJ’s grapheme-color associations for 11 single-color conjuncts and their component consonants.

	Identical		Like 1st?		Like 2nd?		Mix?			Novel Color?	
Components	ন ন	চ চ	ন দ	ণ ড	ম ফ	ক ষ	স ট	ল ট	ঙ গ	ক র	ক ত
Conjunct	ন্ন	চ্চ	ন্দ	ণ্ড	ম্ফ	ক্ষ	স্ট	ল্ট	ঙ্গ	ক্র	ক্ত

We made several additional qualitative observations about MJ’s associations. First, we wondered whether there was a reason that some conjuncts were colored similar to the first vs. second component, and noticed that, for example, “ম্ফ” seems to more closely resemble the second component (“ফ”) than the first (“ম”). Future experiments on larger numbers of synesthetes and conjuncts could ask whether conjuncts were likelier to be associated with the color of a more-similarly-shaped component. Second, we notice that overall, MJ's consonants tended to be "warmer" colors; we wonder if conjuncts are likelier to take the color of the warmer component. This is less farfetched than it sounds; English and Dutch synesthetes are far likelier than non-synesthetes to associate graphemes with colors in the orange-yellow range (Rouw & Root, *in press*). Finally, we wondered about the source of the conjunct color for the two conjuncts without a clear relationship to their underlying components. In our debrief, MJ did give us an interesting post-hoc explanation for her color for "ক্ত": she has a strong memory of first learning to write the conjunct "ক্ত" for the word "blood" ("রক্ত"); perhaps she has associated "ক্ত" with red via a semantic, "Index Route" effect (Mankin and Simner, 2017).

Multicolored conjuncts.

For 9/20 conjuncts, MJ indicated that she experienced more than one color. Of these nine conjuncts, five were quite clearly colored in pieces that aligned with the shapes of the components (e.g., Figure 3a). The remaining 4 conjuncts did not neatly fit into any of the types of associations we predicted. One conjunct was colored in pieces that aligned with the shapes of the components, but the colors of each piece were completely different from the colors of the component consonants. For one consonant, MJ described experienced different pieces as colored differently, including one region in which there was a "gradient"-like transition between each color (Figure 3b). For one consonant, MJ described experiencing a vague "patchy" combination of two colors (Figure 3c) that were not necessarily consistent across time:

> "If I'm forced to choose, I could point to the parts of the grapheme that give me a stronger yellow feeling or a stronger purple feeling, but if I color them that way the end result looks wrong. I'm more comfortable describing the overall texture of the grapheme as if it were draped in a printed fabric with uniformly distributed yellow and purple patches, where the specific positioning of the colors is irrelevant." - MJ on her color for "ক্ষ".

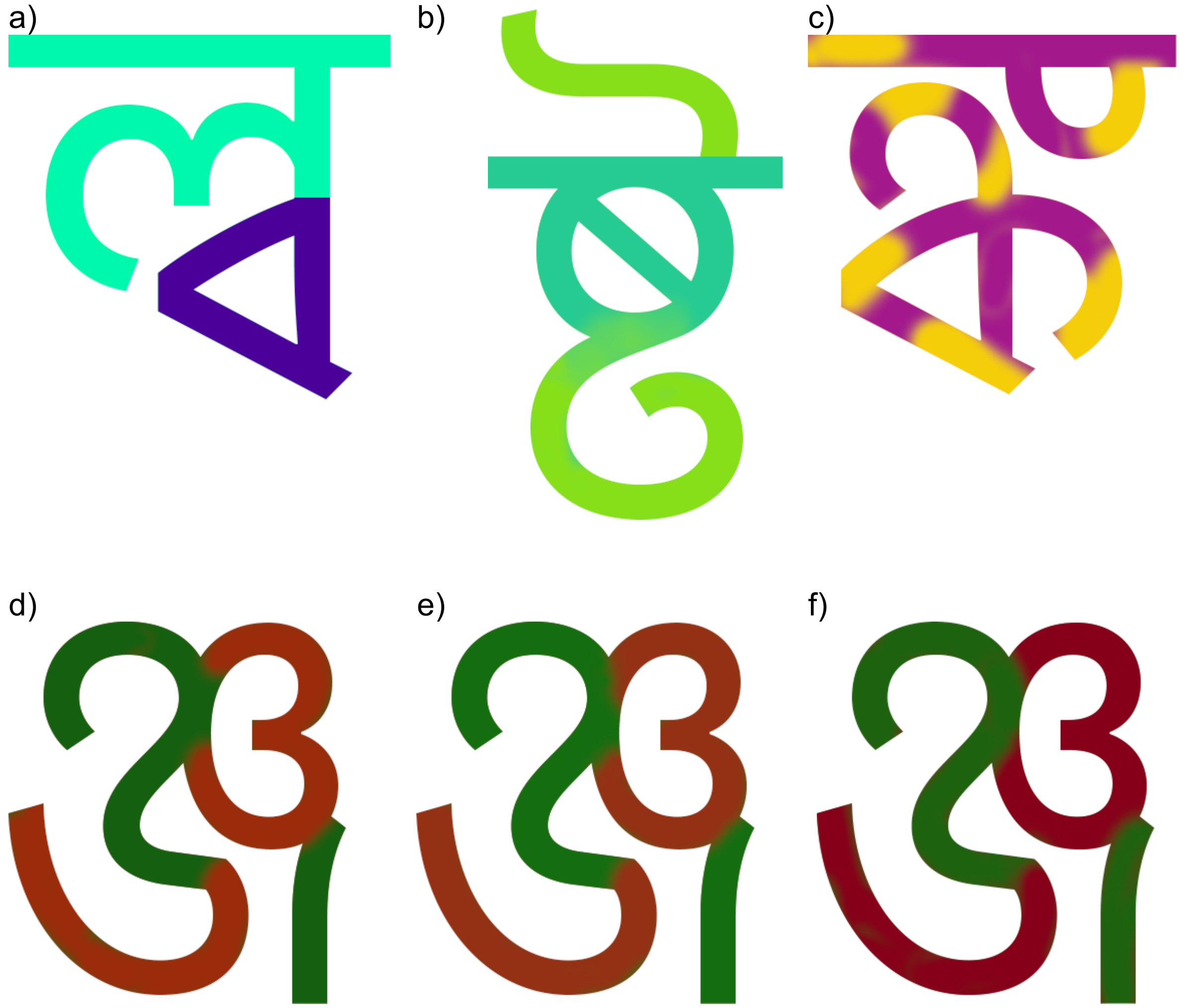


Figure 2.3: Examples of conjunct graphemes with multiple colors. a) a conjunct grapheme with an intuitive coloring, in which the part of the conjunct shape derived from each consonant is associated with the color of that consonant. b) a unique grapheme in which the two colors MJ experiences fade in a "gradient"-like manner. c) a unique grapheme in which MJ cannot verbalize the correct location of the patches; she only knows that both colors are present. d-f) three repetitions of MJ using Photoshop to indicate her phenomenological experience for a multicolored consonant. The first two trials were ~15 minutes apart; the third trial (panel f) was 5 days later.

For the final consonant, MJ experienced "patchy" areas of color that she indicated were better defined, enabling us to assess test-retest consistency of patch location across several days (Figure 3d-f). Not only were the colors of the conjunct consistent, but the location of each piece were remarkably consistent across a test-retest interval of 5 days.

In sum, although MJ's associations give us tantalizing clues about the phenomenological experience of conjunct graphemes, it is clear that there is substantial cross-grapheme variation in her experiences. Ultimately, we must conclude that the color etiology of conjunct graphemes is complex and multifactorial, and any future quantitative analysis of conjunct color will require large numbers of trials and subjects.

EXPERIMENT 3: REGULATORY FACTORS OF MJ'S ASSOCIATIONS

Thus far we have discussed elements of grapheme-color synesthesia in Bengali that are unique to the linguistic features of that language. However, we also sought to test whether grapheme-color synesthesia in Bengali *shares* features with synesthesia in other languages. For example, linguistic properties can act as "Regulatory Factors" (RFs; Asano & Yokosawa, 2011), influencing the specific pattern of grapheme-to-color associations in synesthesia. Do these RFs influence MJ's grapheme-color associations in Bengali?

Below, we test for the presence of two commonly-reported RFs. **First**, similarly-shaped graphemes are associated with similar colors in every language in which the effect has been studied (Brang et al., 2011; Watson et al., 2012; Asano & Yokosawa, 2013). **Second**, similarly-pronounced graphemes are *sometimes* associated with similar colors. Asano and Yokosawa (2011) report that similarly-pronounced kana in Japanese are similarly colored. Similarly, Kang et al. (2017) report that similarly-pronounced Hangul graphemes in Korean are similarly colored (although in Korean shape and sound are confounded; Root et al., 2018). However, in English, similarly-pronounced graphemes are *not* similarly colored (Watson et al., 2012), possibly because English is a particularly-opaque orthography (Asano & Yokosawa, 2013). Bengali has a comparatively transparent orthography, (each grapheme corresponds to a single phoneme that rarely varies from word to word; Sircar and Nag, 2013); furthermore, the first 25 consonants in the Bengali alphabet (বর্গীয় বর্ণ, “classified letters”) are systematically arranged into a two-dimensional ordering: graphemes within a row share place of articulation, graphemes within a column share aspiration, and columns are grouped by the presence of voicing (Anderson, 1917). Therefore, we predicted that sound similarity would influence synesthetic associations in Bengali.

Methods

MJ’s Bengali grapheme-color associations.

If aksara (base consonant plus vowel diacritic) or conjunct consonants were included in these analyses, we would expect to find very strong effects of shape and sound similarity, but this would be problematic because (1) in these characters shape similarity and sound similarity are highly correlated, and (2) these characters have sub-graphemic features with their own colors. Furthermore, the first 25 consonants in Bengali (the “classified letters”) are organized in a highly structured manner, and this structure may confound comparisons between these consonants and other characters. Therefore, we restricted our analysis for Experiment 3 to the 25 “classified letters”. We used the same online color picker as in the previous experiments to collect MJ’s grapheme-color associations for the first 25 base consonant graphemes (the “classified letters”). As in the previous experiments, the color associations were then converted to the CIELuv color space and averaged across the three test-retest repeats.

Shape similarity data.

In previous research, “shape similarity” has been operationalized in more than one way: Watson et al. (2012) use the distance in an 11-dimensional representational space derived from the theoretical letter shape features of Gibson (1969), whereas Brang et al. (2011) use the subjective report data of Courrieu, Farioli, and Grainger (2004), and Asano and Yokosawa (2013) use similar subjective report data for Japanese, reasoning that Japanese kana are too visually-complex to apply Gibson's shape feature analysis. Since Bengali graphemes are also considerably more visually-complex on average than English graphemes (Chang, Plaut, & Perfetti, 2016), we chose to use subjective shape similarity judgements to judge shape similarity.

We recruited 65 undergraduates from UCSD to participate in a Bengali shape-similarity judgement task. All subjects were non-synesthetic native English speakers who could not speak or write Bengali. Each subject performed subjective shape-similarity judgements on a 222-pair subset of the pairwise combinations of the 25 "classified letters". On each trial, subjects saw two graphemes, and a slider that could be adjusted to values between 1-100, with 1 being "completely different" and 100 being "identical". Subjects were instructed not to think too hard (e.g. to not analyze the features of each shape), but rather to indicate their "first impression" of the two shapes' similarity.

Sound similarity

For each pair of the 25 "classified letters", we created a dataset of three boolean variables, coding for whether each pair shared a place of articulation (guttural, palatal, retroflex, dental, labial), whether each pair shared the same aspiration (unaspirated, aspirated), and whether each pair shared the same voicing (voiceless, voiced).

Results

Shape Similarity

To quantify the potential effect of shape similarity on MJ's synesthetic colors, we ran a linear mixed effects model, with pairwise shape similarity judgements as the dependent variable, pairwise Euclidean distance in CIELuv color space of MJ's Bengali graphemes as fixed effect, and subject as random effect. This model explained significantly more variance than a model in which the color distance term was dropped (Likelihood Ratio Test, $\chi^2(1) = 7.59, p < 0.01, \beta = -0.014$).

Sound Similarity

For each pair of the 25 classified letters (consonants classified by these properties), we computed the pairwise Euclidean distance in CIELuv color space of MJ's color associations for the graphemes. We then fit a linear model in which pairwise color distance in CIELuv was modeled as a function of whether the pair shared place of articulation, aspiration, voicing, and each of their two-way interactions[2]. Overall, this model explained 16.74% of the variance in pairwise color distance ($R^2 = 0.17 F(6{,}593) = 19.87, p < 0.001$). Two terms were significant: there was a significant place/voicing interaction ($\beta = -50.55, p < 0.005$), and a significant main effect of voicing ($\beta = -45.01, p < 0.001$); see Figure 4b for a visualization of these effects. Both coefficients were negative; in other words, consonants which share the same voicing are associated with more similar colors, and this effect is exaggerated when they also share the same place of articulation (i.e., they differ only in aspiration).

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[2] The three-way interaction cannot be included, because no pair shares all of voicing, aspiration, and place of articulation.

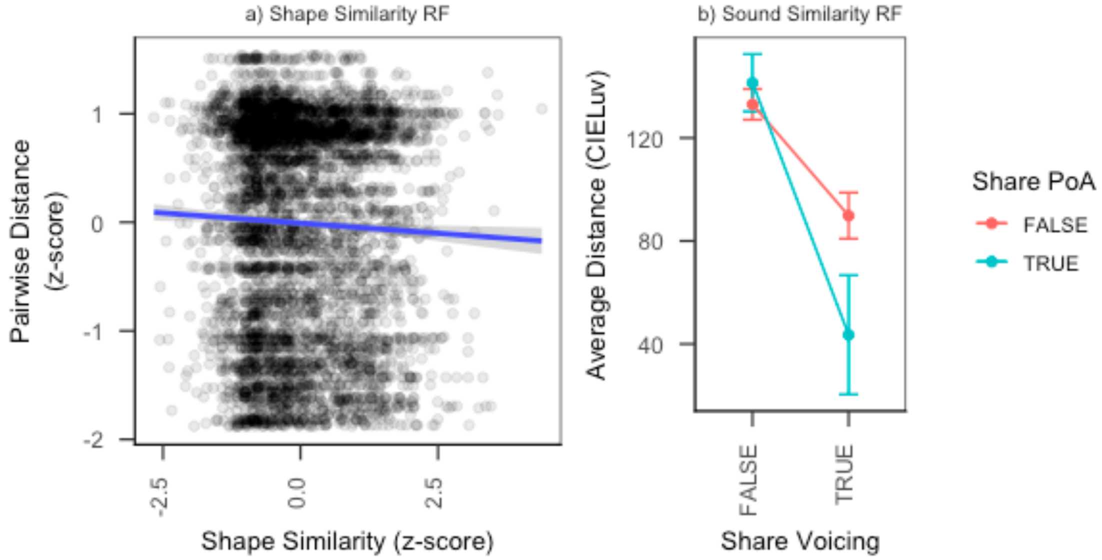

Figure 2.4: Regulatory Factors for MJ's associations. a) Correlation between subjective shape similarity (z-scored) and pairwise distance (z-scored) of MJ's associations. The trend line is of the linear model of pairwise distance as a function of shape similarity (no random effects), ribbon is 95% confidence interval. b) Effect on pairwise distance of MJ's associations of shared voicing (x axis) and shared place of articulation (color). Error bars are 95% confidence intervals.

Discussion

We found that MJ's grapheme-color associations in Bengali were influenced by two Regulatory Factors that are known to influence synesthesia in other languages. Notably, the effect of shape similarity was *very* small compared to the effect of sound similarity; indeed, the difference in pairwise distance between the most similar pairs in the dataset (i.e. shape similarity of 100/100) and the most dissimilar pairs in the dataset (shape similarity of 0/100) is an ~3 unit decrease in pairwise distance. On the other hand, the effect size of sound similarity is quite large: sharing voicing predicts a ~45 unit decrease in pairwise distance. This is consistent with the relative effect sizes of these two RFs in Japanese (Asano & Yokosawa, 2013), another language with visually-complex shapes and a high degree of orthographic transparency. These results are consistent with the "discriminating features" model of Asano and Yokosawa (2013), which proposes that the RFs which most strongly influence a grapheme-color association are those which most consistently discriminate that grapheme from others. In orthographically-transparent languages pronunciation provides a consistently-discriminative cue to grapheme identity, thus the structure of MJ's grapheme-color associations (driven strongly by pronunciation) is consistent with the language-specific features of Bengali (an orthography organized by phonetic features).

GENERAL DISCUSSION

We have described the experiences of a Bengali grapheme-color synesthete, the first report in the literature of synesthesia in an abugida. In some respects, we find remarkable consistency between the phenomenology of MJ's Bengali synesthesia and the phenomenology reported by synesthetes in other languages. For example, at the most basic level, MJ experiences different colors for different graphemes, and those colors are consistent across multiple testing sessions. In addition, MJ's associations are influenced by both grapheme shape and pronunciation, similar to synesthetes in other languages.

However, MJ's Bengali synesthesia also reflects properties of the Bengali writing system that are not present in other languages in which synesthesia has been studied. For example, the color associations for aksara closely resemble the color associations for the base consonant, but are "pulled" towards the color associations for their diacritic's vowel grapheme. It would be interesting to know whether the same effect exists in Arabic, an abjad in which vowels are implicit rather than marked with diacritics. The only study of Arabic synesthesia did not measure separate color associations for consonants in contexts in which the inherent vowel changed (van Leeuwen et al., 2016). If inherent vowels do change the color of Arabic consonants, this might suggest that top-down signals can influence low-level representations of orthography. More speculatively, our results suggest that it may be worth re-examining whole-word color associations in English synesthesia. English-speaking synesthetes who experience a distinct color for each grapheme nevertheless experience a single color for some words during natural reading tasks - typically the color of the initial letter of the word (Baron-Cohen, Harrison, Goldstein, & Wyke, 1993). In the existing literature, small deviation of the word color from the initial letter color is treated as noise; perhaps this data should be re-examined to determine whether the following vowel systematically “pulls” the initial letter color in the same manner as Bengali diacritics.

In addition to the novel findings about diacritic structure, it is also noteworthy that MJ can experience conjunct consonants as having *either* single colors or multiple colors. It is exceedingly rare for English-speaking synesthetes to experience multiple colors for the same grapheme (Hubbard & Ramachandran, 2005), so the relative frequency of this phenomenon in MJ’s conjunct consonants (45% of tested conjuncts were associated with more than one color) is quite distinct from synesthesia in English. It is also distinct from the experience of Korean synesthetes, who nearly always associate syllable blocks with the color of the onset phoneme (Shin & Kim, 2014), but is more similar to the experience of synesthetes for Japanese Kanji (Hamada, Yamamoto, & Saiki, 2017), which can be associated with multiple colors. It is interesting to consider the implications of these findings for theories of grapheme representation: does the brain represent single-color conjuncts as unique graphemes with their own abstract identity, whereas multi-colored conjuncts are represented as simultaneous activation of the two consonants from which they are composed? Alternatively, do the differences between conjunct color types resemble the differences between English words perceived with their individual letters vs. English words perceived as a single color (Blazej & Cohen-Goldberg, 2016)? More generally, a question left unanswered by the present report is why some conjuncts are associated with a single color and others are multicolored. Future research using larger sample sizes should test whether the same conjuncts are multicolored across subjects, and if so, whether some regulatory factor predicts *which* conjuncts are multicolored.

It is important to emphasize that our study is a single-subject case study with several significant limitations. Most critically, some synesthetic phenomenology cannot be studied without a large sample size; for example, grapheme-color trends (a particular grapheme is more likely to be associated with a particular color) require many subjects, so we cannot ask whether some grapheme-color associations in Bengali are more common than others. In addition, even though MJ has charitably spent numerous hours participating in our experiments, it would take far more hours than she could give to collect her grapheme-color associations for every Bengali grapheme (e.g., if aksara sharing a base consonant are considered different graphemes - which Experiment 1 suggests should be the case - then there are more than 500 unique associations to measure. At the pace of the average synesthete in our studies, it would take MJ more than 10 hours to provide grapheme-color associations three times for all graphemes). Future research using large number of synesthetes could overcome this issue by collecting a randomly-chosen subset of associations from each subject, so that in the aggregate each combination could be examined.

Finally, one other limitation of our study is that MJ is a native bilingual who was exposed to both Bengali and English from birth. It is conceivable that MJ's language history influenced the nature of her Bengali associations (indeed, there is some subjective evidence that English associations might have "seeded" a few of MJ's Bengali associations - for example, MJ's /b/ is blue in both languages, and “B” is commonly blue in English-speaking synesthetes). Ideally, future research on Bengali synesthetes would seek synesthetes for which Bengali was the sole native language. However, numerous schools in India begin teaching English in the first year of instruction; indeed, English is the primary language of instruction in many Indian schools (“English-medium” schools), particularly schools for the middle- and upper-class (Faust & Negar, 2001), who are probably more likely to come into contact with synesthesia researchers. Thus, it may not be possible to find “pure” native Bengali speakers. One potential alternative for future research would be to attempt to compare synesthetes who learn English relatively early *vs.* relatively late; if the phenomenology of Bengali synesthesia is consistent across these groups then it is probably not an artifact of the influence of their L2 English.

In sum, we have described several novel features of grapheme color synesthesia in Bengali, an abugida. We describe the results of a single subject MJ, but several effects we report are highly significant and have large effect sizes even at the level of a single synesthete. Future research can illuminate which features of MJ’s synesthesia generalize to all Bengali synesthetes. More generally, the idiosyncratic phenomenology of MJ’s synesthesia reflects idiosyncratic properties of the Bengali writing system, and reinforces the need for more cross-language studies of synesthesia. As we improve understanding of the relationship between synesthetic associations and the neural representation of graphemes, it may one day be possible to leverage these idiosyncrasies to understand how the properties of a language change not only synesthetic phenomenology, but also the underlying reading systems in the brain.

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CHAPTER 3

The Synesthete Within: Consistent, synesthesia-like grapheme-color associations in "non-synesthetes"

Root, Nicholas; Ramachandran, V.S.

ABSTRACT

Grapheme-color synesthetes experience letters of the alphabet as having a consistent color. There is a long-standing debate in the synesthesia research community about the degree to which synesthetic associations are comparable to "normal" cross-modal associations. On the one hand, phenomenological descriptions of synesthesia seem obviously distinct from our everyday experiences. On the other hand, when forced to choose a color for a letter, non-synesthetes' choices are not random. What, then, makes synesthesia "special"? Is there a synesthete in all of us?

In the present work, we show that many non-synesthetes experience "synesthesia-like" associations for a small subset of their letters. These associations are "synesthesia-like" in color: non-synesthetes share the same patterns of associations between *certain* letters and *certain* colors. These associations are "synesthesia-like" in consistency: non-synesthetes choose the same color across three test-retest repetitions. Finally, these associations are "synesthesia-like" in subjective report: non-synesthetes are confident that their choice is the "best color" for the letter. Across three of the most defining properties of synesthesia, differences between synesthetes and non-synesthetes appear to be differences in degree, not in kind.

INTRODUCTION

Grapheme-color synesthetes experience letters of the alphabet as having a consistent color (e.g., a synesthete might say that "The letter 'R' is sky blue."). There is a long-standing debate in the synesthesia research community about the degree to which synesthetic associations are comparable to "normal" cross-modal associations (Kadosh & Henik, 2007; Deroy & Spence, 2011). On the one hand, phenomenological descriptions of synesthesia seem obviously different from our experience of cross-modal associations such as “loud” shirts (we do not *actually hear* the shirt, whereas synesthetes *actually see* the color; Palmeri, Blake, Marois, Flanery, & Whetsell, 2002). On the other hand, when forced to choose a color for a letter, non-synesthetes’ color choices (*which* color is *which* letter) sometimes resemble those of synesthetes (Simner et al., 2005).

Previous studies have compared synesthetes to non-synesthetes, but have only done so at the level of a single trial: non-synesthetes each generate a single color for each letter, and the pattern of responses is compared to the responses of synesthetes (e.g., Rouw, Case, Gosavi, & Ramachandran, 2014). This analysis demonstrates that non-synesthetes make some “synesthesia-like” *color choices*, but leaves unanswered the question of whether non-synesthetes have some letters with “synesthesia-like” *consistency*.

In the present study, we sought to clarify these questions by giving a true test-retest consistency task to non-synesthetes. We designed an online color-picker similar to the Eagleman Synesthesia Battery (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007), which enabled non-synesthetes to choose colors for letters, and also to indicate how confident they were that their choice reflected the “best color” for the letter. With these measures, we can explore whether there is a difference between the *experience* of being a synesthete from the *consistency* of a grapheme-color association. What, if anything, makes synesthesia “special”? Is there a synesthete in all of us?

EXPERIMENT 1: DO NON-SYNESTHETES MAKE “SYNESTHESIA-LIKE” COLOR CHOICES?

We first sought to replicate the reports of Mankin et al (2005) and Rouw et al (2014), that patterns of non-synesthetic association resemble patterns of synesthetic association. For example, both synesthetes and non-synesthetes tend to associate “A” with red (Root et al., 2018).

Methods

Non-Synesthetes.

We designed an online color picker that was functionally similar to the Eagleman Synesthesia Battery (Eagleman et al., 2007), the most commonly-used online tool for test-retest measurement. On each trial a letter of the alphabet is presented (in random order), and subjects are prompted to use the color picker to choose the color that they associate with the letter. After choosing colors for every letter, the process repeats an additional two times. Our color picker differed from the Eagleman Battery in two respects. First, the Eagleman Battery allows subjects to select “No Color” (this is because synesthetes do not always experience a color for every letter, Ramachandran & Hubbard, 2001); we force subjects to choose a color because otherwise the modal answer for non-synesthetes should be “No Color” for every trial. Second, we included an additional measurement for every trial, of subject confidence. After choosing the color association for a letter, subjects were prompted to use a sliding scale to indicate their confidence in their choice, from 1 (“I feel like I am guessing”) to 100 (“I am certain that this is the best color”).

60 UCSD undergraduates were recruited to participate in the experiment. Subjects were native English speakers with normal or corrected-to-normal vision. Subjects were directed to our

online color picker, and instructed to choose the “best color” for each letter. We emphasized that they should not think too hard or use an explicit strategy, but rather choose the color that “first comes to mind” for each letter.

From this data, we first excluded any potential synesthetes. We computed the overall test-retest consistency of each subject: subjects qualified as non-synesthetes if the average of the sum Euclidean pairwise distance in CIELuv between repeated trials was greater than 135 (consistency less than 135 is considered synesthetic, Rothen et al, 2013). By this criterion, we excluded 9 subjects as potential synesthetes. Our final dataset contained data from 51 non-synesthetes.

From this data, we further calculated the per-letter test-retest consistency for each letter for each subject (i.e., how consistent were non-synesthetes’ choices for a *single* letter?) by computing the sum Euclidean pairwise distance in CIELuv between the three trials. Finally, each association was also categorized into the 11 Berlin-Kay basic colors (Berlin & Kay, 1969) using the synthetic observer of Mylonas et al (2013), a machine learning algorithm that was trained with a large number (1,000,000+) of human color naming trials to make “human-like” color categorizations.

Synesthetes

Data were from 54 synesthetes from a previous experiment (data and procedure described in Rouw & Root, *in press*). The dataset contained the average color reported by each synesthete for each letter, in CIELuv space. From this data, we categorized each association into the 11 Berlin-Kay basic colors (Berlin & Kay, 1969) using the same synthetic observer as with the non-synesthete data above. Finally, we aggregated Berlin-Kay color choices across subject, yielding a 26x11 matrix of counts of each Berlin-Kay color for each letter.

Results

To determine whether synesthetic and non-synesthetic associations were more similar than chance, we first transformed counts to chi-squared residuals to eliminate the confound of base rate: both synesthetes and non-synesthetes report more associations for "primary" colors red/blue/green/yellow than "secondary" colors purple/pink/orange/brown (Rouw & Root, *in press*); thus, if base rate is not controlled, correlations between synesthetic and non-synesthetic associations will be inflated. We ran 26 chi-squared goodness of fit tests, one for each letter, with the null hypothesis that the distribution of color associations for that letter came from the overall probability distribution of colors for the entire alphabet. Large positive residuals on this test for a particular combination of letter and color would indicate that color was likelier to be associated with that letter *in particular* (i.e., controlling for base rate across all letters). This yielded a list of 286 residuals (26 letters x 11 Berlin-Kay colors) for synesthetes' associations. We then repeated the same exact procedure for the non-synesthetes data, yielding a list of 286 residuals for non-synesthetes' associations.

To test whether synesthetes' specific grapheme-color associations (the propensity to associate *particular* letters with a color) are similar to non-synesthetes' grapheme-color associations, we computed the correlation of the synesthetes' and non-synesthetes' residuals. Residuals for both synesthetes and non-synesthetes were highly non-normal (Shapiro-Wilk test, both $p < 0.001$), so we used Spearman rank correlation; there was a significant correlation between the associations of synesthetes and non-synesthetes ($p < 0.001$, $\rho = 0.40$).

To explore the source of these correlations, we examined the chi-square residuals for each letter for which the omnibus chi-squared statistic was significant (Bonferroni corrected for

26 comparisons; 12 letters for synesthetes, 10 letters for non-synesthetes). For these letters, we computed standardized chi-squared residuals, which can be treated as a z-statistic and Bonferroni corrected to yield slightly-conservative estimates of significance for cellwise post-hoc tests (MacDonald & Gardner, 2000). By this criterion, we found 11 associations that were significant in both synesthetes and non-synesthetes (A - red, B - blue, G - green, I - white, P - pink & purple, R - red, X - black, Y - yellow, Z - black), five associations that were significant only in synesthetes (C - yellow, O - black, O - white, V - purple, X - grey), and one association that was significant only in non-synesthetes (W - white).

EXPERIMENT 2: DO NON-SYNESTHETES HAVE "SYNESTHESIA-LIKE" CONSISTENCY FOR THEIR "SYNESTHESIA-LIKE" COLOR CHOICES?

In previous studies comparing synesthetes to non-synesthetes, non-synesthetes made a single color choice. What would happen if they were forced to choose again? One possibility is that non-synesthetes resemble synesthetes at the group but not the individual level; e.g., 40% of non-synesthetes at t_1 associate "A" with red, 40% of non-synesthetes at t_2 associate "A" with red, but it is a *different* 40%. Another possibility is that non-synesthetes are also "synesthesia-like" in consistency: e.g., 40% of non-synesthetes at t_1 associate "A" with red, and the *same* 40% of non-synesthetes at t_2 associate "A" with red. In an exploratory visualization of non-synesthete color choices for "A" (Figure 1), we noticed that the pattern of associations is more suggestive of the latter hypothesis: a group of non-synesthetes consistently associates "A" with red. Here, we quantify this effect across all of the "synesthesia-like" grapheme-color associations from Experiment 1. Do non-synesthetes have "synesthesia-like" consistency for their "synesthesia-like" associations?

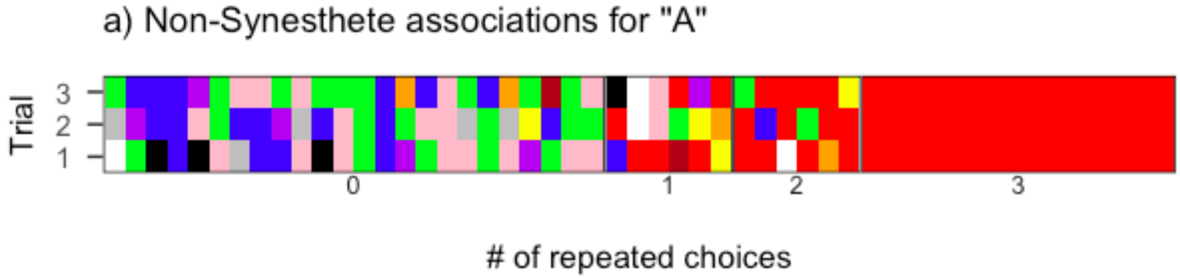

Figure 3.1: Trial-level non-synesthete data for "A". Each column is a subject; each row is a test-retest repeat of the trial for "A". Subjects are grouped along the x axis by number of their choices that were consistent with the "synesthete-like" color for "A" (red).

Methods

Data are the non-synesthete data collected in Experiment 1. This dataset was then filtered to include only the 10 letters for which there was a statistically-significant grapheme-color association that was shared between synesthetes and non-synesthetes: A (red), B (blue), G (green), I (white), P (pink, purple), R (red), X (black), Y (yellow), and Z (black).

Results

We defined "synesthesia-like consistency" as three repeated choices of the same color. On average, when non-synesthetes reported a "synesthete-like" color for a letter, they chose the same color for that letter on all three repeats 31% of the time. To quantify how likely it would be for such consistency to occur by chance, we constructed a null hypothesis distribution using Monte Carlo resampling with 10000 repetitions, shuffling the subject label between repeated trials. In this way, the overall distribution of color choices for the letter was preserved, so differences between this statistic and our observed consistency can only be attributed to within-subject consistency, rather than to a high base-probability of choosing the color. Non-synesthetes' synesthesia-like color choices were significantly more consistent than would be expected by chance (Figure 2; permutation test, 10000 replications, $p_{expected} = 0.048$, $p_{observed} = 0.31, H0\ 95\%\ CI: [0.027, 0.069], p < 0.001$).

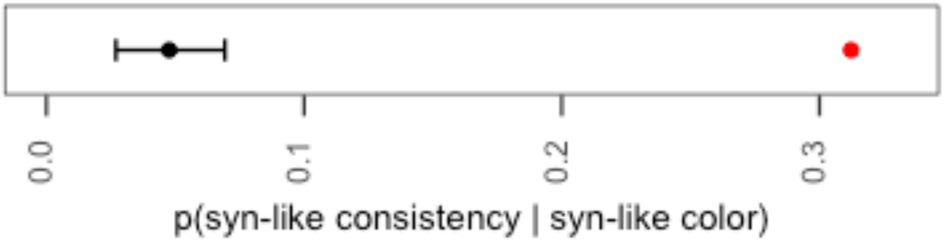

Figure 3.2: The distribution of average proportion of letters with "synesthete-like" consistency (same color on all three repeats) that would be expected by chance(Monte Carlo resampling, subject ID shuffled between trials, 10000 repetitions). The red point indicates the observed proportion of letters with "synesthete-like" consistency.

Discussion

Test-retest consistency is a defining feature of synesthesia that is often used as the "gold standard" for verifying a subject's synesthesia status. Yet, we find that when non-synesthetes associate letters with "synesthete-like" colors, they are also much more likely than chance to experience "synesthete-like" consistency for those color choices. Why, then, do these subjects not qualify as synesthetes by test-retest consistency measures? The answer is that any given non-synesthete only experiences a small number of these consistent associations; the *average* of their test-retest consistency across all letters is far too inconsistent to be considered synesthetic. Such variation in test-retest consistency across letters is typically considered to be noise or random variation (e.g. non-synesthetes making a "lucky guess"), but we have shown that it is in fact signal: non-synesthetes experience more consistent associations than they "should", and the associations they *do* experience are similar to those of synesthetes. For *some* letters, non-synesthetes and synesthetes cannot be distinguished using test-retest consistency.

EXPERIMENT 3: ARE NON-SYNESTHETES AWARE OF THEIR “SYNESTHESIA-LIKE” ASSOCIATIONS?

Another defining feature of synesthesia is the subjective experience of *certainty* that a particular letter is a particular color. Synesthetes feel that their choice is “correct” (Ramachandran & Hubbard, 2001), and we have often observed two synesthetes who disagree about the color of a letter each exasperated with the clearly illogical experience of the other! We wondered if non-synesthetes, for the subset of letters for which they have a “synesthesia-like” associations, also feel that their choice is “correct”. When we collected non-synesthetes’ color choices in Experiment 1, non-synesthetes also rated confidence in their choice on each trial, from 1 (“I feel like I am guessing”) to 100 (“I am certain that this is the right color”). Here, we ask: on the trials in which non-synesthetes picked a “synesthesia-like” color with “synesthesia-like” consistency, were they also more confident that it was the “right color” for the letter?

Methods

Data are the same as in Experiment 2. We further aggregated across test-retest trials within-subject: for each subject, for each letter, we recorded the number of repeats in which the subject reported the “synesthesia-like” color (1, 2, or 3), and the subject’s average confidence rating that the “synesthesia-like” color was the “best color” for the letter.

Results

Figure 3a depicts average subject confidence that their chosen color is the “best color”. Non-synesthetes who chose the “synesthesia-like” color for all trials (i.e., “synesthesia-like” consistency) were significantly more confident that the color was the "best" color than those who chose the color once ($t(155.03) = 4.13, p < 0.001$) or twice ($t(114.09) = 3.59, p < 0.001$).

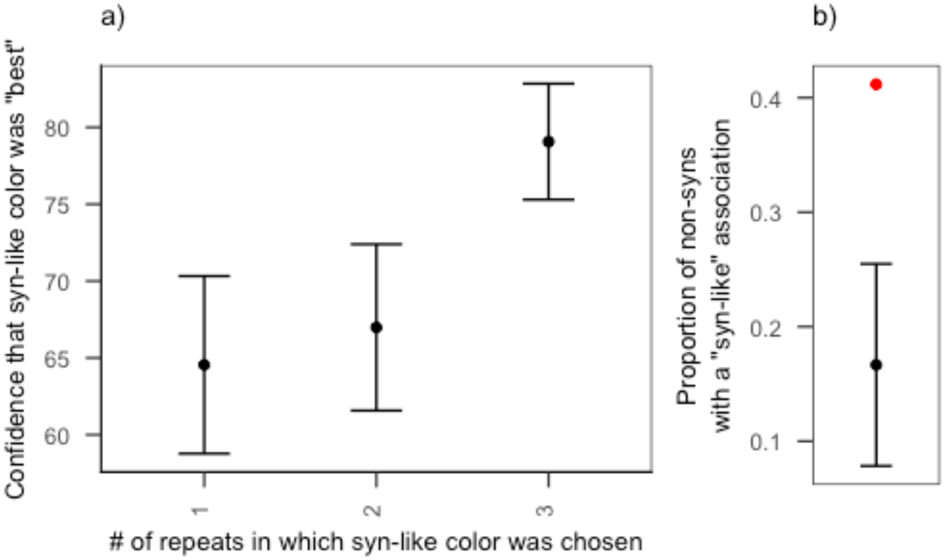

Figure 3.3: a) Subjects' confidence ratings as function of how "synesthesia-like" their associations are (x=3 is "synesthesia-like consistency"). Error bars are 95% CI. b) The distribution of proportion of non-synesthetes with at least one "synesthesia-like" association ("synesthesia-like" color, consistency, and certainty) that would be expected by chance (Monte Carlo resampling, subject ID shuffled between trials, 10000 repetitions). The red point indicates the observed proportion of non-synesthetes with at least one "synesthesia-like" association.

We wondered what proportion of non-synesthetes in our sample experienced at least one of these "synesthesia-like" associations. We operationalized "synesthesia-like" certainty as having a confidence rating greater than 75 (roughly the lower bound of the 95% confidence interval for trials with "synesthesia-like" consistency). In our sample, 21/51 non-synesthetes (41%) experienced at least one "synesthesia-like" association ("synesthesia-like" color, consistency, and certainty). To quantify how likely it would be for so many non-synesthetes to experience a "synesthesia-like" association by chance, we constructed a null hypothesis distribution using Monte Carlo resampling with 10000 repetitions, shuffling the subject label between repeated trials. Significantly more non-synesthetes experienced at least one "synesthesia-like" association than would be expected by chance (Figure 3b; permutation test, 10000 replications, $p_{expected} = 0.17, p_{observed} = 0.41, H0\ 95\%\ CI: [0.078, 0.25], p < 0.001$).

Discussion

We found that non-synesthetes' "synesthesia-like" associations ("synesthesia-like" color and consistency) are likelier to elicit the sensation that the color is the "best color" for the letter. One trivial explanation for this is that several associations shared between synesthetes and non-synesthetes have cognitively accessible explanations ("B" is blue, "R" is red, etc.). However, this cannot be the whole story, because the etiology of many associations is more opaque: synesthesia researchers know that "I" and "X" are white and black because of their shapes (Spector & Maurer, 2011), but it is exceedingly unlikely that non-synesthetes could verbalize *why* "A" is red, or "I" is white, or "X" is black, etc. Yet, non-synesthetes clearly feel that these colors are the "best" colors for these letters. This sense of certainty is reminiscent of the reports of associator-type synesthetes, who "know" that a particular letter is a particular color, but do not actually *see* the letter as colored (Dixon, Smilek, & Merikle, 2004). Associator synesthetes readily describe themselves as having synesthesia, whereas subjects in our study do not. Clearly, for most letters, our non-synesthetes do *not* look synesthetic. However, for a small subset of letters, synesthetes and non-synesthetes seem indistinguishable by means other than subjective verbal report.

GENERAL DISCUSSION

The phenomenological experience of synesthesia seems profoundly discrete: either you experience a letter as having a color, or you do not. In verbal reports, people rarely have difficulty classifying themselves as synesthete or non-synesthete. Here, we have shown that for several of the "defining" features of synesthesia, non-synesthetes have the same experiences as synesthetes for a small subset of their letters.

Synesthetic associations were once considered idiosyncratic; indeed, some theories of synesthesia explicitly separate it from "normal" cross-modal processing on the basis of synesthetic associations being idiosyncratic (Deroy & Spence, 2011). However, research using large samples of synesthetes has demonstrated clear patterns in the specific colors synesthetes associate with specific letters (Simner et al., 2005; Rich, Bradshaw, & Mattingley, 2005). We replicate previous reports (Mankin et al., 2005, Rouw et al., 2014) that synesthetic and non-synesthetic grapheme-color associations are highly correlated. This correlation could not be explained by the base rate of choosing colors across all letters, because we correlated chi-squared residuals rather than raw proportions or counts. Furthermore, of the 12 significant grapheme-color associations in non-synesthetes, only one was not shared with synesthetes. Given the high degree of overlap, and small (singular) number of unique non-synesthetic associations, our results strongly support a shared etiology of specific color associations in synesthetes and non-synesthetes. Contrary to the theoretical claims of Deroy and Spence (2011), our data clearly show that some grapheme-color associations in non-synesthetes are very much like grapheme-color associations in synesthetes.

Synesthetic associations are highly consistent across time (Asher, Aitken, Farooqi, Kurmani, & Baron-Cohen, 2006); indeed, test-retest consistency measures are considered the "gold standard" operationalization of synesthesia. Non-synesthetes in our study were less consistent *overall* than synesthetes: indeed, we used this operationalization to remove any potential synesthetes from our data. However, for the subset of letters that non-synesthetes associated with “synesthesia-like” colors, many non-synesthetes were so consistent over time as to be indistinguishable from synesthetes.

The last refuge of bimodality in synesthetic *vs.* non-synesthetic experience is surely subjective experience: the feeling of “what it is like to be a synesthete”. Indeed, no non-synesthete in our study reported that they actually “*saw* colors on a letter” (i.e. projector-type synesthesia). And yet, for the subset of letters for which non-synesthetes had “synesthesia-like” color and consistency, many of them *knew* the letter should be that color: they were confident that they had picked the “best color” for the letter. What do we make of this? In some ways, this distinction speaks to questions of qualia and the nature of consciousness. Our results suggest that synesthetes might consciously “see” what the rest of us (consciously or unconsciously) “know”. Perhaps someday synesthesia can help reveal the neural mechanisms that lead to “knowing without seeing” versus actually experiencing qualia.

On a more practical level, future work must reconcile our present observation of a high correlation between synesthetes’ and non-synesthetes’ specific grapheme-color associations with a previous observation that synesthetes and non-synesthetes have distinct *overall* patterns of color choices (i.e. different base frequencies across letter; Rouw & Root, *in press*). Explaining why synesthetic associations sometimes look similar and sometimes look different is critical for any attempts to generalize findings from synesthesia to the (much larger) non-synesthetic population. To the extent that specific grapheme-color associations are influenced by linguistic properties (e.g., Asano & Yokosawa, 2013), these properties should be shared between synesthetes and non-synesthetes, which would explain consistent *similarities* between synesthetes and non-synesthetes. What could account for consistent *differences*? One potential explanation is that synesthetic associations (which color is which letter) typically begin to "crystallize" in early development (around ages 6/7, Simner, Harrold, Creed, Monro, & Foulkes, 2008). If the influences that drive biases towards specific grapheme-color associations change throughout development, then synesthetes and non-synesthetes could have different associations. In Chapter 4 (from Root, Dobkins, Ramachandran, & Rouw, *in press*), we develop a novel test of this hypothesis.

In the present work, we show that many non-synesthetes experience "synesthesia-like" associations for a small subset of their letters. These associations are "synesthesia-like" in color: non-synesthetes share the same patterns of associations between *certain* letters and *certain* colors. These associations are "synesthesia-like" in consistency: non-synesthetes choose the same color across three test-retest repetitions. Finally, these associations are "synesthesia-like" in subjective reports: non-synesthetes are confident that their choice is the "best color" for the letter. Across three of the most defining properties of synesthesia, differences between synesthetes and non-synesthetes appear to be differences in degree, not in kind.

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Chapter 3, in full, is currently being prepared for submission for publication of the material. Root, Nicholas; Ramachandran, V.S. The dissertation author was the primary investigator and author of this paper.

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CHAPTER 4

Echoes from the Past: Synesthetic Color Associations Reflect Childhood Gender Stereotypes

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ABSTRACT

Grapheme-color synesthesia is a neurological phenomenon in which linguistic symbols evoke consistent color sensations. Synesthesia is believed to be influenced by both genetic and environmental factors, but how these factors interact to create specific associations in specific individuals is poorly understood. In this paper, we show that a grapheme-color association in adult synesthetes can be traced to a particular environmental effect at a particular moment in childhood. We propose a model in which specific grapheme-color associations are "locked in" during development in children predisposed to become synesthetes, whereas grapheme-color associations remain flexible in non-synesthetes. We exploit Western gender-color stereotypes to test our model: we found that young girls *in general* tend to associate their first initial with the color pink. Consistent with our model, adult female synesthetes are influenced by their childhood environment: they associate their first initial with pink. Adult female non-synesthetes do not show this bias. Instead, in our study non-synesthetes tended to associate their first initial with their *current* favorite color. The results thus support the "locking in" model of synesthesia, suggesting that synesthetic associations can be used as a "time capsule", revealing childhood influences on adult linguistic associations. Grapheme-color synesthesia may thus offer an extraordinary opportunity to study linguistic development.

INTRODUCTION

Grapheme-color synesthesia is a phenomenon in which graphemes elicit specific, and automatic sensations of color: a synesthete might say that "The letter R is sky-blue." Synesthetic associations are a genuinely perceptual experience – they really do *see* the colors (Ramachandran & Hubbard, 2001; Palmeri, Blake, Marois, Flanery, & Whetsell Jr., 2002). Synesthetes typically find these additional experiences pleasant and useful – synesthesia is not related to a psychological, psychiatric or neurological "disease". Synesthetes report having had their grapheme-color associations for as long as they can remember, and their specific associations (which letter is which color) are consistent across months or even years (Asher, Aitken, Farooqi, Kurmani, & Baron-Cohen, 2006). Synesthesia is thought to be related to excess connectivity between brain regions, , and brain imaging studies have found both structural and functional brain connectivity differences between synesthetes and controls (van Leeuwen et al, 2011; Zamm et al., 2013; Rouw & Scholte, 2007; Sinke et al, 2012; Banissy et al 2012; for a review see Rouw, Scholte, & Colizoli, 2011). Synesthesia tends to run in families: 42% of synesthetes report a first-degree relative with synesthesia (Barnett et al 2008; see Brang & Ramachandran, 2011 for a review), and studies suggest that the propensity to develop synesthesia is partly, but not completely, attributable to genetics (Asher et al., 2009; Tomson et al., 2011; Tilot et al., 2018).

Nevertheless, the specific grapheme-to-color associations of a synesthete (which letter is which color) cannot be attributed to genetic predispositions, since graphemes are part of a culturally-defined, learned writing system – we are not born knowing letters. Indeed, previous studies have provided concrete examples of letter-color combinations in certain synesthetes that can be explained by toys from the synesthete's childhood, such as "colored alphabet" refrigerator magnets (Witthoft & Winawer, 2013; Witthoft, Winawer & Eagleman, 2015; but see also Rich et al., 2005)[3]. Thus, although the *propensity* to develop synesthesia is plausibly genetic, the *specific manifestation* (including *which* letter is associated with *which* color) is shaped by environment and learning influences (Barnett et al., 2008; Newell & Mitchell, 2016). However, the exact

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[3] Similar findings have been obtained in other types of synesthesia; for example, linguistic and conceptual knowledge shapes associations in lexical-gustatory synesthesia (Ward & Simner, 2003).

nature of this interaction is not yet known: how does the synesthetic trait shape the particular letter-to-color experiences that set synesthetes apart from non-synesthetes? Several models explore the relationship between genes and environmental influences, attributing differences between synesthetes and non-synesthetes to differences in implicit learning mechanisms (Bankieris & Aslin, 2017; Bankieris et al., 2018), to particular idiosyncratic differences in white matter structure (Rouw & Scholte, 2007; Newell & Mitchell 2016), and to conditioned mental imagery in response to letters (Witthoft & Winawer, 2013; Witthoft et al., 2015). Understanding the underlying mechanisms is not only interesting in its own right, but can also offer important insights into how a particular gene-environment interaction can result in a "different" conscious experience.

This question becomes even more relevant when considering that grapheme-color associations are not unique to synesthetes: non-synesthetes, when forced to choose a color for a grapheme, share some patterns of grapheme-color associations with synesthetes (Simner et al., 2005; Rouw, Case, Gosavi, & Ramachandran, 2014; Mankin & Simner, 2017). However, studies comparing synesthetes and non-synesthetes show that while some patterns of grapheme-color associations are shared, others are unique to synesthetes or non-synesthetes (Simner et al., 2005). These seemingly contradictory findings have led to a debate about the degree to which synesthetic associations are "different" from crossmodal associations in non-synesthetes (e.g., Martino & Marks 2001; Brang, Kanai, Ramachandran, & Coulson, 2011; Simner, 2012; Eagleman, 2012; Deroy & Spence 2013; Watson, Akins, Spiker, Crawford, & Enns, 2014). Why would some patterns of grapheme-color association be unique to synesthetes, whereas others are present in both synesthetes and non-synesthetes?

As several authors have pointed out, to answer this question and fully understand the synesthetic condition, it is necessary to understand how synesthesia develops during childhood (Watson et al., 2014; Newell & Mitchell, 2016; Witthoft et al., 2015) Currently, only a few studies have examined synesthesia in children. These important studies showed that average consistency – taken as the "gold standard" in diagnosing synesthesia – is relatively low in synesthetic children at age 6/7, and increases by age 10/11 (Simner et al., 2008; Simner & Bain, 2013). Synesthetic children with colored numbers also showed learning and memory deficits when to-be-remembered numbers were written in a color incongruent with their own synesthetic colors (Green & Goswami, 2008). Together, these findings suggest both protracted development of synesthesia, and reduced flexibility in synesthetes as compared with non-synesthetes. This links synesthesia to literature on functional specialization (Newell & Mitchell, 2016): over time, a particular function, such as face recognition (Haan, Pascalis, & Johnson, 2002) or letter and phoneme perception (Werker & Tres, 1984; Brem et al., 2010), becomes more fixed and fluent at the expense of flexibility. The current study builds upon and extends previous models of differences between the synesthetic and non-synesthetic developmental processes. In particular, we show that the combination of protracted development and reduced flexibility in synesthetes makes a testable prediction about why letter-color associations in synesthetes and non-synesthetes are sometimes similar and sometimes different.

We propose that genetically-determined differences in synesthetes (e.g., increased connectivity, Tilot et al, 2018) do not cause grapheme-color associations per se, but instead cause existing, environmentally-influenced grapheme-color associations to be strengthened and "locked in": made stable over time. As a result of this "locking in" mechanism, synesthetes, when asked to report a grapheme-color association for an experiment, will report an association that was formed *at a specific moment in development*. In contrast, non-synesthetes, whose associations were never “locked in”, report an association that they *generate in the present moment*. This model can account for both similarities and differences in the associations of synesthetes and non-synesthetes. Associations will be the same when the *current* influences on adult non-synesthetes create the same color as the *childhood* influences did in synesthetes. They are different when this is not the case; for example, associations which were present in childhood but not adulthood, should influence the grapheme-color associations of adult synesthetes, but not adult non-synesthetes.

To test this prediction, it would be necessary to find an association between a letter and a color that is common in children *in general* – in both synesthetes and non-synesthetes – during the time period in early childhood when synesthetic associations begin to develop and become increasingly consistent (Simner et al., 2008; Simner & Bain, 2013). During exploratory analysis of previously-collected data from a small group of adult American synesthetes, we observed an association that we believe satisfies these constraints: female synesthetes in our dataset seemed unusually likely to associate their first initial with the color pink.

In early childhood, pervasive cultural stereotypes cause girls to associate their gender identity with the color pink. As early as 2.5 years of age, girls prefer pink items (e.g., toys, room furniture, and clothing) and boys actively *avoid* pink items, and children between 3 and 5 years of age will judge that pink-colored items are “for girls” (Cunningham et al 2011; LoBue & DeLoache, 2011). These gender-specific color preferences develop in stages: after learning about gender-related characteristics in preschool years, children demonstrate highly rigid beliefs about stereotypic sex typing – peaking between 5-7 years of age (Huston, 1985). Crucially, these gender-color associations weaken significantly after this peak as children’s beliefs become increasingly tolerant and flexible (Trautner et al., 2005). Thus, during early childhood, but not adolescence or adulthood, color becomes an implicit gender label, where pink is “for girls” while the absence of pink is “for boys”. In this study, we test the hypothesis that the gender-color stereotype “pink is for girls” influences girls’ grapheme-color associations, and is “locked in” in female synesthetes, but disappears in adult female non-synesthetes.

EXPERIMENT 1: YOUNG GIRLS ASSOCIATE THEIR FIRST INITIAL WITH PINK

The first initial is the closest proxy for an individual’s identity of any letter. Children typically learn their first initial of their first name before other letters from the alphabet, and use the first initial to distinguish their name from other names (Treiman & Broderick, 1998). Since young girls have a preference for the color pink in situations related to their own identity, we predict that young girls will associate their first initial with the color pink. We sought to test this prediction in girls aged 5-7 who did not show any signs of synesthesia. We excluded potential synesthetes from this experiment because a key assumption of our model is that the propensity for girls to associate their first initial with pink is not caused by the synesthetic trait.

Methods

Data from 17 girls ages 5 – 7 (mean age = 5.76 years) in San Diego were recruited from a child database via an email which asked parents to participate with their child in an online study. Our sample size was determined solely by the size and response rate of our child database, but our sample size of 17 yields 89.9% power to detect an effect equal to that observed in our exploratory analysis of adult English-speaking synesthetes (this effect size, as well as the others reported in the paper, were calculated using the *power.fisher.test* function in R’s *statmod* package, with 100,000 simulations each). With the help of their parents, children completed a simplified color matching task modeled after Simner et al. (2008; see Supplemental Figure S1), in which they matched six letters of the alphabet to 12 colors (we included all Berlin-Kay basic colors except black, plus a dark variant of blue and green to match the test of Simner et al., 2008). One of the letters was the child's first initial, and the other 5 (selected from the letters A, B, E, R, T, Y) were included to estimate the proportion of the time pink would be chosen for letters that were not the first initial. Participants were then administered a surprise retest after a short break. In the current study, we wanted to exclude potential child synesthetes, so we excluded one subject whose consistency on the retest was statistically-significantly higher than average (the same cutoff used by Simner et al., 2008). We further planned to exclude any subject with the first initial "P" – since "P" is commonly associated with pink in adult synesthetes and non-synesthetes (Simner et al., 2005) – but none of our subjects had the first initial "P" (i.e., 0 subjects excluded). From this data ($N = 16$), we used only the first set of responses made by each of the 16 children included in the analyses; we reasoned that non-synesthetic subjects' responses on the first trial were least likely to be contaminated by previous answers.

Results

Qualitatively, non-synesthetic girls were likelier to choose pink for their first initial than for other letters. Of all reported associations for letters other than the first initial (80 associations total, 5 for each subject), 7.5% were with the color pink (Figure 1, left pink dot). Of all reported associations for the first initial (16 associations total, one for each subject), 31.3% were with the color pink (Figure 1, right pink dot). The critical effect here is not the proportion of pink for the first initial (31.3%), but rather *relative* preference for pink: the first initial is 4.17 times likelier to be pink than other letters[4]. To quantify this observation, we ran a Fisher exact test to determine whether color association (pink *vs*. not pink) was dependent on letter (first initial *vs*. not first initial). Non-synesthetic girls associate their first initial with pink significantly more often than they associate other letters with pink ($p = 0.0173$, Risk Ratio $RR = 4.167$).

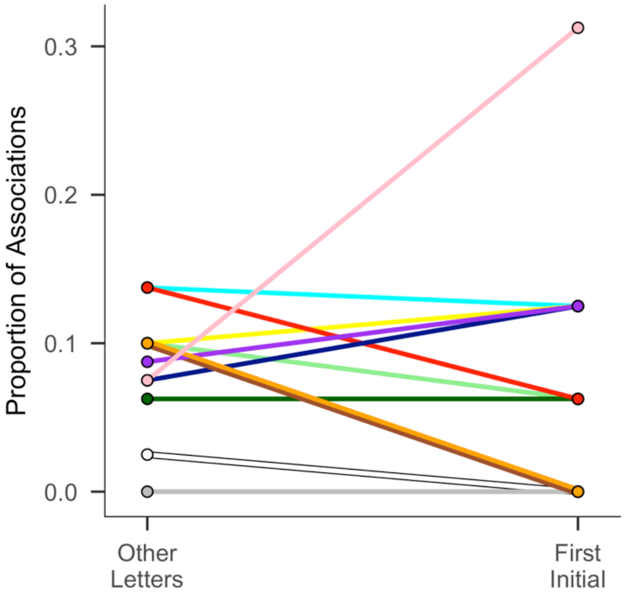

Figure 4.1: The proportion of associations between a letter and each of the 12 color choices, for non-synesthete girls, for the first initial (right) and for all other letters (left). The first initial is likelier than other letters to be associated with pink.

EXPERIMENT 2: ADULT FEMALE SYNESTHETES, BUT NOT NON-SYNESTHETES, ASSOCIATE THEIR FIRST INITIAL WITH PINK

Having shown that young girls tend to associate their first initial with the color pink, we next sought to test our primary hypotheses. First, we predict that during childhood, female

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[4] One concern is that since color names influence trends in adult grapheme-color associations (Simner et al., 2005), existing trends – "B" is blue/brown, "R" is red, "Y" is yellow – might lead us to underestimate the true proportion of pink associations in our control letters. However, by Fisher exact tests, our child non-synesthetes do not associate "B" with blue/brown ($p = 0.076$), "R" with red ($p = 0.11$), or "Y" with yellow ($p = 0.19$) more than would be predicted by chance. Thus, we have no evidence that trends in the control letters confound the results of Experiment 1.

synesthetes “locked in” the association between their first initial and pink, and thus that adult female synesthetes’ will associate their first initial with pink more often than expected by chance. Qualitatively, this was true in our exploratory analysis; here, we will quantify this observation in our full dataset of English-speaking synesthetes, and also aim to replicate our finding in a dataset of Dutch-speaking synesthetes. In addition to cross-validating our exploratory result, this would also allow us to test if our findings generalize cross-culturally and cross-linguistically. Second, we predict that synesthetes are different from non-synesthetes: female non-synesthetes do not “lock in” any grapheme-color associations during childhood development, so adult female non-synesthetes will *not* associate their first initial with pink more often than expected by chance. We will test this prediction in both Dutch and English non-synesthetes.

Methods

Synesthetes. We analyzed grapheme-color associations in a combination of data from synesthetes used in a previous study (Root et al., 2017) and newly-collected data. All subjects had completed the Eagleman Synesthesia Battery (synesthete.org), a standardized battery for Synesthesia (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) and qualified as synesthetes using the test-retest consistency threshold which maximizes sensitivity and specificity, derived in Rothen, Seth, Witzel, & Ward (2013): average Euclidean distance in CIELuv of test-retest associations less than 135 (smaller numbers indicate more consistent associations). In total, data from 78 English-speaking synesthetes and 157 Dutch-speaking synesthetes contributed to this study. We excluded from our data any synesthete who did not report a consistent color for at least 50% of graphemes (14 English- and 36 Dutch-speaking synesthetes excluded). We further excluded subjects who were male or for whom gender information was not present (20 English- and 21 Dutch-speaking synesthetes excluded), and subjects who did not report a color for their first initial (5 Dutch-speaking synesthetes excluded). Finally, we excluded 3 English-speaking subjects who chose black for more than 80% of their letters, suggesting that they misunderstood the task and chose the printed grapheme color; and 3 English-speaking subjects who admitted using memorization tricks to artificially increase their consistency score rather than providing their natural associations. Our final dataset contained 38 female English- and 95 female Dutch-speaking synesthetes (mean consistency in CIELuv = 70.48, consistency range [27.87 - 130.04]).

Non-synesthetes. We collected data from 60 English-speaking and 24 Dutch-speaking university students. Subjects completed the Eagleman synesthesia battery, but were given adjusted instructions to account for the fact that they were reporting abstract associations rather than perceptual experiences. We explained synesthesia, and explained that the test they were taking was meant for synesthetes, but in this study would be used to study how non-synesthetes associated colors. We asked the non-synesthetes to report which color is best for the letter, and emphasized that they should not think cognitively or use an explicit strategy, but rather report the "first color that came to mind" for each letter. We also emphasized that the task might seem strange to them, but that there is no "right" or "wrong" answer. We processed this data in the same way as with synesthetes: we excluded subjects who did not report a color for at least 13 letters (i.e. 50% of the alphabet; 3 Dutch-speaking and 3 English-speaking subjects excluded), any subject that was male or of unknown gender (19 English- and 5 Dutch-speaking subjects excluded), any subject that did not choose a color for their first initial (0 subjects excluded), and any subject who chose the same color for more than 80% of letters (0 subjects excluded).

Additionally, as in Experiment 1, we analyzed only the first trial for each grapheme. Our final dataset contained 38 English-speaking non-synesthetes and 16 Dutch-speaking non-synesthetes.

For data from both synesthetes and non-synesthetes, we transformed the provided color associations (256 x 256 x 256 possible colors) into the 11 basic color terms of Berlin and Kay (1991) using a previously-collected dataset of 1,354 colors that were categorized into the Berlin-Kay color categories by 1,177 subjects (Jraissati & Douven, 2018). For each grapheme-color association in our dataset, the association was categorized as the modal Berlin-Kay color term used by Jraissati & Douven's subjects for the color in their dataset with closest Euclidean distance in CIELuv to our subjects' reported colors.

We used the effect size from our exploratory analysis from the English-speaking synesthetes to estimate the power of our sample sizes, and obtained an estimate of 99.9% power for the Dutch synesthete data, 93.7% power for the Dutch non-synesthete data, and 99.9% power for the English non-synesthete data.

Results

Qualitatively, synesthetic females (Figure 2, black lines) look like non-synesthete girls (Figure 2, dotted line): they are much likelier to associate their first initial with pink than to associate other letters with pink (English: 4.4 times likelier; Dutch: 3.6 times likelier). To quantify this observation, for each language we ran a Fisher exact test to determine whether color association (pink *vs*. not pink) was dependent on letter (first initial *vs*. not first initial). Both English- and Dutch-speaking synesthetes associate their first initial with pink significantly more often than they associate other letters with pink (English: $p < 0.001$, $RR = 9.226$; Dutch: $p <$

0.001, *RR* = 5.242). This effect remains highly significant when data from both languages are combined ($p < 0.001$, *RR* = 6.621)

For non-synesthetes, color association (pink *vs.* not pink) does not seem to depend on letter (first initial *vs*. not first initial) as much as in synesthetes. Again, the important measure is not the absolute proportion of pink first initials but rather the *relative* preference: we are measuring how much *likelier* the first initial is to be pink, compared to other letters. For example, the proportion of pink first initials is similar in Dutch synesthetes and non-synesthetes (Figure 2, right panel, right dots), but the base rate of pink letters is much higher in Dutch non-synesthetes than in Dutch synesthetes (Figure 2, right panel, left dots), so the effect of first initial vs. other letter is much stronger in Dutch synesthetes. To quantify this observation, we ran the same analysis on non-synesthetes as on synesthetes (Fisher exact tests). Indeed, for both Dutch- and English-speaking non-synesthetes, there was not a statistically significant relationship between color association and letter: they do *not* associate their first initial with pink significantly more often than they associate other letters with pink (English: $p = 0.067$, *RR* = 2.36; Dutch: $p = 0.635$, *RR* = 1.51). Importantly, this null result is not likely to be caused by a lack of statistical power: as mentioned in the methods, we had 94% power in Dutch and 99% power in English to detect an effect as large as that observed in synesthetes. Indeed, even when data from both languages are combined we do not see a statistically significant relationship ($p = 0.085$, *RR* = 2.03). We do note that the relationship between first initial and pink is marginally significant in English (and thus trending in the combined dataset); however, the effect size is quite small compared to in synesthetes[5].

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[5] To verify that the effect is stronger in synesthetes than non-synesthetes, we ran a logistic mixed effect regression with color (pink *vs.* other) as dependent variable, letter status (first initial *vs.* other) and synesthesia status (synesthete *vs*. non-synesthete) as fixed effects, and subject as random effect. As predicted, the letter*synesthesia interaction was significant (Wald $z = 2.7$, $p = 0.007$)

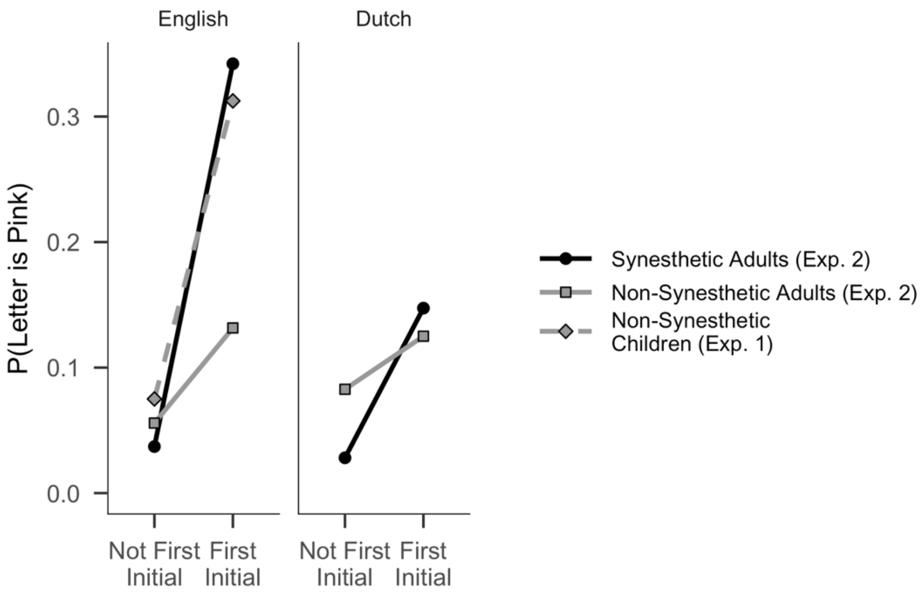

Figure 4.2. The proportion of letters associated with pink, for the first initial vs. all other letters (x axis), in synesthetes vs. non-synesthetes (black vs. grey), and in English vs. Dutch (left vs. right panel). The dotted grey line depicts the data from non-synesthetic girls from Experiment 1 (this line is the same as the pink line in Figure 1).

We also performed an additional *post-hoc* analysis to control for the possibility that our non-synesthetes did not take the test seriously (i.e., chose colors randomly): we tested whether non-synesthetes associated "A" with red, a frequently-reported association in non-synesthetes (e.g. Simner et al., 2005; Rouw et al., 2014). Consistent with previous research, our non-synesthetes associated "A" with red significantly more often than they associated other letters with red (Fisher Exact tests; English: $p < 0.001$, Dutch: $p = 0.011$). Since graphemes in the task were presented in random order, it seems unlikely that our subjects were engaged in the task when "A" was presented, but not when their first initial was presented.

EXPERIMENT 3: NON-SYNESTHETES ASSOCIATE THEIR FIRST INITIAL WITH THEIR FAVORITE COLOR

In Experiment 2, we established that non-synesthetic adult females do not associate their first initial with pink more than would be expected by chance. This is consistent with our model: we propose that non-synesthetes generate their associations at the time of the test, and the association between female and pink disappears by adulthood (Trautner et al., 2005). Could the color associated with non-synesthetes' first initial now be influenced by a different factor? Here we perform a *post-hoc*, exploratory test, hypothesizing that non-synesthetes would associate their "special" first initial letter with their current favorite color.

Methods

Several weeks after they were initially tested, we re-contacted all English-speaking adult female non-synesthetes, asking them to indicate their favorite of the 11 Berlin-Kay colors. Three of the 38 original subjects did not respond, yielding a total of 35 subjects.

Results

Consistent with the weakening of gender-color stereotypes with age (Huston, 1983; Trautner et al., 2005), English-speaking adult female non-synesthetes were no likelier than chance to pick pink as their favorite color (Binomial test, $p = 0.628$). Consistent with our hypothesis, English-speaking female non-synesthetes associate their first initial with their current favorite color significantly more often than they associate other letters with their favorite color

(Fisher test, $p = 0.048$, $RR = 2.345$)[6]. Figure 3 depicts this result, plotted together with the data from Experiment 2; the synesthetes' data from Experiment 2 (dotted pink line) more closely resembles the non-synesthetes' favorite color data (solid black line) than the non-synesthetes' pink data from Experiment 2 (solid pink line). In other words, while adult synesthetes were influenced by a childhood color association, this association is not present in non-synesthetes. Instead, it was replaced by an association with their current favorite color, an influence present at the moment the non-synesthetes were tested.

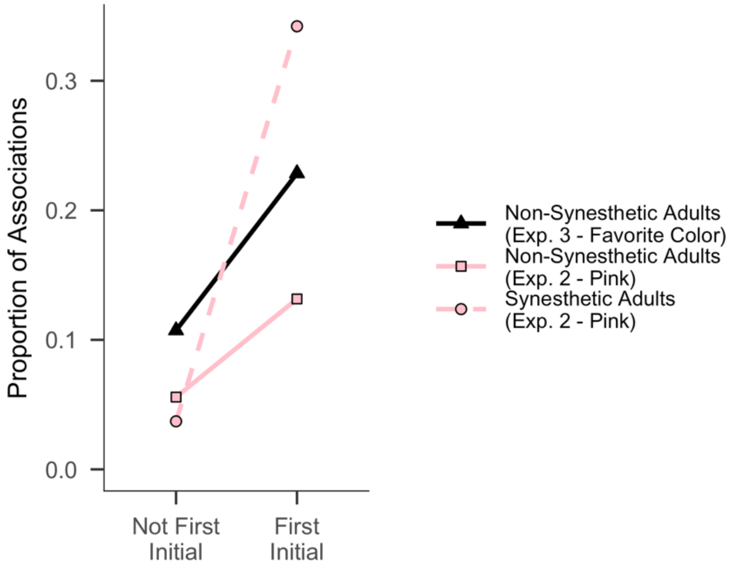

Figure 4.3. The black line depicts the proportion of letters associated with the favorite color (y axis), for the first initial vs. all other letters (x axis) for English-speaking non-synesthetes. The pink lines depict the data from English-speaking subjects in Experiment 2 (these lines are the same as the solid lines in the left panel of Figure 2): the proportion of letters associated with pink (y axis), for the first initial vs. all other letters (x axis), in synesthetes vs. non-synesthetes (dotted vs. solid).

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[6] We noticed that of the five adult non-synesthetes who chose pink, two indicated that pink was still their favorite color; the marginally-significant trend for English non-synesthetes to associate their first initial with pink could instead be driven by these subjects' favorite color.

GENERAL DISCUSSION

We find that in both Dutch and English samples, female synesthetes associate their first initial with the color pink more often than expected by chance. In contrast, adult non-synesthetes do not associate their first initial with pink more than would be predicted by chance; instead, they associate their first initial with their current favorite color. This is consistent with a model in which environmental factors evoke associations between grapheme and color in all people (children, adults, synesthetes, non-synesthetes), but only individuals with the genetic predisposition to develop synesthesia "lock in" particular associations during development, creating the stable associations in adulthood that are typical of synesthesia. Our results demonstrate how differences in the pattern of grapheme-color associations in synesthetes and non-synesthetes can be attributed to changes in environment across the lifespan: associations that are unique to synesthetes in adulthood (e.g. in Simner et al., 2005) may actually be present in non-synesthetes during early childhood, but disappear during development, whereas these associations are maintained in synesthetes. More generally, our results demonstrate how a shared environmental factor in childhood can have differential effects on adult cognition, depending on genetic predisposition for synesthesia.

What is the neural basis of the "locking in" effect in synesthetes? A growing number of studies demonstrate that learning a particular task increases both brain connectivity and brain volume in the brain areas most relevant to that task (Maguire et al., 2000; Draganski et al., 2006; Loui et al., 2011). How these changes relate to adaptations at the level of the brain is not yet understood. One possible mechanism of "locking in" is at the level of neurons: when synesthetic individuals experience associations between grapheme and color – the same associations that we all experience – their additional neuronal connectivity might cause self-reinforcing patterns of activity (e.g., “Hebbian” learning; see also Newell & Mitchell, 2016). As a result, associations between grapheme and color are quickly strengthened in synesthetes in a “winner-take-all” (Kaski & Kohonen, 1994) fashion, whereas non-synesthetes maintain more flexible associations. This explanation is in line with research showing stronger implicit learning in synesthetes as compared with non-synesthetes (Rothen et al., 2013; Watson et al., 2014; Bankieris & Aslin, 2017; Bankieris et al., 2018). In addition, it is consistent with the finding that average consistency is relatively low in young synesthetic children and increases with age (Simner et al., 2008; Simner & Bain, 2013). Taking all these lines of evidence together, synesthetic associations in early childhood should go from flexible to increasingly solid and consistent, due to the “locking in” process taking place over time in childhood.

This proposal leads to testable predictions: the differential developmental pattern of “locking in” color associations can explain more than just this “pink initial” effect. It should be possible to attribute other differences between synesthetic and non-synesthetic color associations to the time period in which the associations were formed (e.g. children read different words/texts than adults). In turn, non-synesthetes are relatively more flexible; this can be examined in the 'training synesthesia' paradigm. Non-synesthetes might “lock in” more permanent associations if the input is strong and consistent enough to overcome their lack of genetic predisposition. Indeed, strong training programs can mimic synesthetic behavior and even brain functions (Bor et al., 2014; ; Colizoli et al., 2014; Colizoli, et al., 2017), although training programs thus far have not induced a permanent “locking in”: the effects in existing research stop several months after the end of training (Bor et al., 2014).

Future research could extend current findings beyond female English and Dutch speakers, who share relatively similar language features. It would be interesting to see if results replicate in very different cultures and languages, though we would predict that our results *only* replicate in cultures where "pink is for girls" (pink is only as special as a culture decides it to be). In addition, since boys have a preference *against* pink (LoBue & DeLoache, 2011), male synesthetes should *not* associate their first initial with pink[7]. Furthermore, researchers with databases of child synesthetes (which requires screening very large numbers of children) could confirm that, at a young age, child synesthetes and child non-synesthetes generally share the same pattern of associations, including associating the first initial with pink.

Another important question for future research is why *certain* associations lock in sooner than others: Simner et al.'s (2008) study of childhood synesthesia found that only 29% of synesthetes' letters/digits are consistent by ages 6/7. Indeed, in our child data, three strong, well-replicated trends in adults, blue/brown "B", red "R", and yellow "Y" (Simner et al., 2005; Rich et al 2005; Mankin & Simner, 2017), were not present yet[2]. This suggests that the obtained pink first initial effect is amongst the earliest associations to be "locked in" - plausibly because children learn their first initial before they learn other letters (Treiman & Broderick, 1998). Thus, the order in which associations "lock in" could provide valuable insights into the acquisition of reading skills during development.

In sum, we report the first example of grapheme-color associations in adult synesthetes that could be traced back to grapheme-color associations measured in non-synesthetic children. We show how these environmentally-influenced associations in early childhood are later "locked in" for synesthetes, but not for non-synesthetes. An exciting prospect for future research is that by measuring particular influences on synesthetic color associations across different ages,

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[7] Indeed, 0/11 of our English-speaking male synesthetes associated their first initial with pink, but a sample size of at least 500 would be required to test for significance at 80% power.

synesthetes can be used as a “time capsule” to trace the development of specific linguistic, cognitive, and perceptual representations to specific moments in development.

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Chapter 4, in full, is a postprint of the material as it will appear in *Philosophical Transactions of the Royal Society B*. Root, Nicholas; Dobkins, Karen; Ramachandran, V.S.; Rouw, Romke.

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