It was a red day in a green month. The peppery sounds of the piccolo floated out of the doors of the band room. Late, I sprinted through the door of my seventh grade science classroom, muttering an apology and my teacher's name, a soft purple sprinkled with flecks of sandy brown. The class began as usual, boring rainbow words spilling out of his grim mouth. Suddenly, a sky-blue colored word fell off his tongue that would turn my world upside down: synesthesia.

Synesthesia, he said, is the union of senses otherwise unconnected in a “normal” brain. He described Albert Einstein using shapes instead of numbers to complete mathematical algorithms, and briefly scoffed at the absurd idea of colored letters. Could it be that none of my classmates saw our teacher’s name in purple with flecks of sandy brown? Were A’s not inherently fire-truck red nor Z’s metallic gray? Didn’t everyone find it efficient to memorize phone numbers according to their unique color palates?

Confused and bewildered, I stumbled home, repeating over and over the word my teacher had mentioned so nonchalantly: synesthesia, synesthesia, synesthesia. Powering up my computer, I immediately began to read every article I could find on this mysterious “disorder,” “disease,” “condition,” or “superpower.” It seemed as though researchers did not even know how to classify my sixth sense. As it turns out, every day of my life, I've been wearing rainbow-colored glasses. Cemented to my eyes like irremovable contact lenses, they turn letters into colors, music into tastes, and time into space.

I burst out of my room, interrogating my parents to find out if they too saw B as indigo or K as lavender. They stared at me dumbfounded, undoubtedly questioning my sanity. It was in that moment, a blue hour and an orange minute, that I made my decision to discover *why* A is red, *why* rap music is salty, and *why* my perception of the world around me is invariably tinted by my beloved rainbow-colored glasses.

I continued reading every article I could find on this neurological phenomenon, excited each time my inbox ping!-ed from the Google Scholar alert I had set to automatically notify me as new synesthesia articles were published. As my overzealous classmates dreamt of curing cancer or solving the global energy crisis, I emailed the authors of every synesthesia paper I had ever read to request an opportunity to work in their labs. I watched dejectedly as my inbox teemed with responses full of “regretfully” and “unfortunately.”

After weeks tinged periwinkle by disappointment, a postdoctoral researcher embraced my enthusiasm and disregarded my age and inexperience. Several phone interviews later, I had my first job as a research assistant in a vision sciences laboratory. My research flourished, and I was astonished by the positive responses from the community as I presented at professional conferences and received national awards.

Sipping my tea one morning, the pages of the New York Times rustling, my heart beat at an inhuman speed as I saw my own neurophysiological theory for synesthesia typeset beneath the “Science Times” heading. With my own research paper now being reviewed for publication in *Psychological Science*, it is dizzyingly exciting to think that before the end of the year, my email will ping! with an alert for my very own scientific journal.

When I was recently contracted to write the definition of synesthesia for the *Encyclopaedia Britannica*, I realized that the search for understanding and the years of dogged inquiry have provided meaning and answers to my colorful questions. My synesthesia has always defined me, and now I can define it.

Grapheme-color synesthesia, specifically, is a form of synesthesia in which an individual's perception of numbers and letters is associated with colors. For this reason, in all I hear or read, I see each letter in an individual assigned color. Weekdays and months are also colored and specifically aligned spatially. My mind, the epitome of a visual aid, could be one in 10,000. I find it impossible to fathom a mind void of synesthesia- colors create experiences for me that are not only interesting, but also motivating. This "sixth sense" provides the impetus to understand the differing perspectives of each individual. In my quest to comprehend humans' most complex feature, the brain, I strive to ascertain an interpretation of the various thought processes available to the mind, synesthetic or not.

Synesthetes do not simply imagine or purposefully associate colors with letters. One line of evidence for this comes from comparisons of the brain activity of natural synesthetes to so-called "forced synesthetes" — people who have been taught to recall a certain color whenever a paired letter or word is heard. Using fMRI, researchers found that different parts of the brain are activated in the two types of synesthetes when they associate colors with letters or words. In the natural synesthetes, visual areas V4 and V8 are active (Nunn et al., 2002). These areas are critically involved in the perception of color. In forced synesthetes, in contrast, only auditory processing areas were active, which suggests that they were only processing the auditory stimuli rather than simultaneously receiving visual involuntarily (Nunn et al., 2002). Consistent with this neuroimaging evidence, most contemporary models of synesthesia agree that it involves communication between cortical areas that are not otherwise connected in non-synesthetes (Bargary, 2007).

Previous work has considered factors that affect which color associations are most common. A 2007 review aggregated data from past experiments on synesthesia to draw several conclusions about the role of gender, genetics, and demographic variables in determining common color associations (Barnett et al., 2007). Another 2007 study considered the role of early perceptual experience by examining the relationship between grapheme frequency and color luminance in grapheme–color synesthetes. The results showed that the luminance of synesthetic colors increases with the frequency of digits in everyday language and that the saturation of synesthetic colors increases with increased letter and digit frequency, demonstrating that synesthetic associations are affected by the prevalence of the grapheme and how often it is encountered in printed text (Beeli et al., 2007).

I carried that idea a step farther by considering the relationship between a letters' prevalence in English, Spanish, and German and the hue of the color that is most commonly associated with it. Because these languages share many graphemes, but use them in different proportions, it is possible to distinguish effects of frequency from those of letter shape.

In Experiment 1, I measured the correlation between the frequency of a letter in the English, Spanish, and German languages and the hue of the color associated with it by a majority of synesthetes. If a synesthete's associations depend on their personal experience, then the color–letter associations of synesthetes would be governed by the letter frequencies of their own language. Thus, I considered English-, Spanish- and German-speaking synesthetes. These three languages share many letters, but use them in different proportions. To estimate letter-color associations for the English language, I used the *Common Letter-Colour Associations* chart (Barnett et al., 2007), which aggregates color–letter associations found in other studies, highlighting cases where the majority of synesthetes have the same color–letter association. For the Spanish language, data from a deidentified pool of Spanish grapheme-color synesthetes asked to choose the color that most closely represents their association with each letter was used.

Spanish was used because letters have different frequencies in the Spanish language and correspondingly different colors. Similarly, for the German language, data from a study conducted in Germany (Emrich, Schneider, Zedler, 2004) was used to deduce the wavelengths of the colors German synesthetes (*n*=89) most typically associate with letters and was graphed against the frequencies of these letters in the German language. For each colour-letter association in each language, I decomposed the letter into its hue, saturation, and luminance. While the focus of this study was on the relationship between letter frequency and hue, I also analyzed the relationship between letter frequency and saturation for comparison purposes.

For English, letter frequencies were estimated using three different sources. First, letter frequencies were tallied from the words of the Oxford English Dictionary. In this dictionary, E is the most frequent letter (11.2%) and Q is the least frequent letter (0.196%). Though the dictionary does represent the composite English language as a whole, each word is included a single time and the prevalence of words in writing is not taken into account. For example, "the" is used in nearly every sentence, yet the dictionary only lists it once. However, the constant use of "the" in writing could cause a synesthete to associate a lower frequency color with the letters "t," "h," and "e." Therefore, in a second analysis, I used letter frequencies from the Brown Corpus, an anthology of the English language that includes excerpts from English literature, speeches, and music. The Brown Corpus represents a more accurate cross-section of the printed language that an adult synesthete experiences in daily life (Roland et al., 2007). Lastly, because a synesthete's grapheme–color associations are formed in childhood (Eagleman, 2007), I compiled a corpus of ten popular children's books, which is perhaps a better representation of childhood experience with printed text.

The reported correlations between color and letter frequency are circular-linear correlations between hue and log letter frequency. Hue is specified as an angle on the color wheel and is thus a circular dimension (hence the use of the circular-linear correlation). Effects of frequency are most commonly measured in log units, e.g., in Zipf's law (Zipf, 1935).

The frequency of a letter was highly correlated with the hue of the color most commonly associated with it in the English, Spanish, and German language (Figures 1 and 2). For English-speaking synesthetes, correlations were strongest with letter frequencies derived from the dictionary (r^2 = 0.66), slightly weaker from children's books (r^2 = 0.57), and weakest from the Brown Corpus (r^2 = 0.45).

Critically, for each language, stronger correlations were found with the letter frequencies that matched the synesthetes' experience with printed text (i.e., those from their native language) than with letter frequencies that do not match their experience (i.e., those from other languages). For example, nearly every German synesthete sees "N," one the most common letters in the German language, as red (Emrich, Schneider, Zedler, 2004). On the other hand, most English-speaking synesthetes would see "N", an average frequency color in the English language, as green.

Further analyses showed a very weak correlation between letter frequency and perceived saturation (r^2 = 0.16).

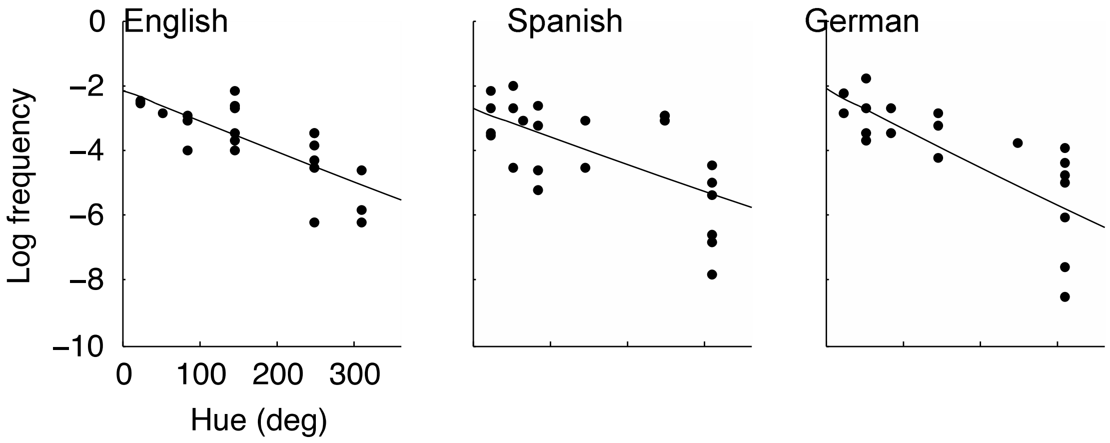

Figure 1. Circular correlations between hue and letter frequency. Plots depict circular–linear correlations between hue and log frequency.

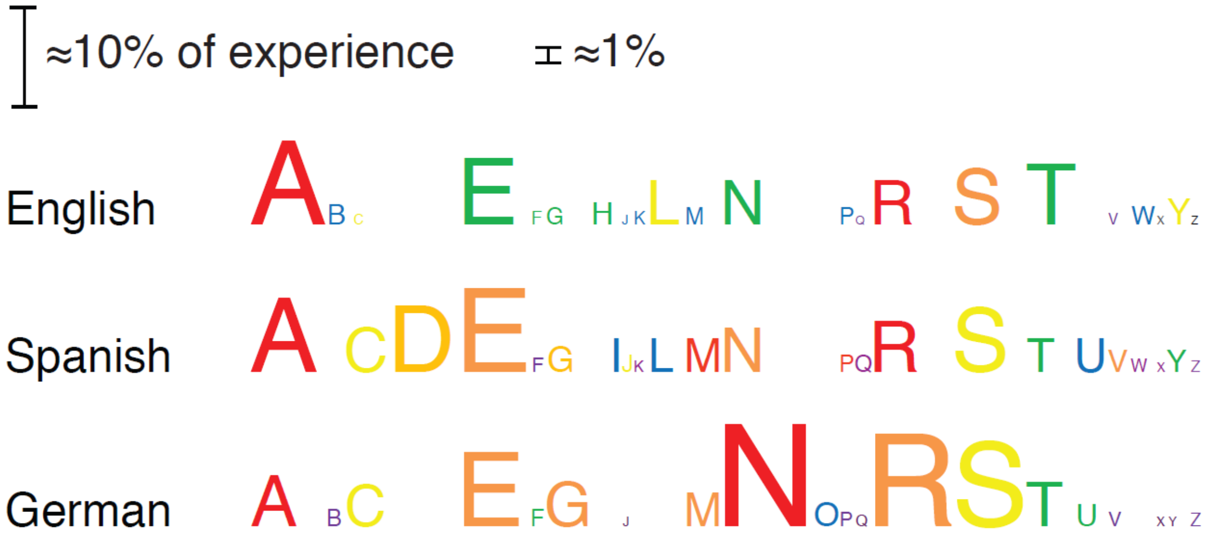

Figure 2. Letter frequencies and associated colors. The size of the letter represents its frequency: larger size denotes more frequent letters, smaller size denotes less frequent letters. Letters are shaded in the color associated by a majority of synesthetes native to that language. One can see that the larger letters tend to be longer wavelength colors, such as red and orange, while the smaller letters tend to be shorter- wavelength colors, such as blue and purple. (Some letters are excluded due to their predominant hue being indeterminate, such as brown or gray)

It is possible that there is a strong relationship between letter frequency and color because high frequency letters occur within high frequency color terms. I performed an additional analysis to test this possibility. Color term frequencies for each color in each language were determined by their frequency in printed text (Google N-gram viewer). A partial correlation analysis was then performed measuring the correlation between hue and letter frequency controlling for color term frequency; the correlation between letter frequency and color held for English and German, and was marginal for Spanish (Table 1).

Table 1. Partial correlations between color hue and letter frequency, controlling for color term frequency.

	English	Spanish	German
r	0.69	0.48	0.68
p	0.0070	0.072	0.0098

As there is a slight correlation between letter frequency and order in the alphabet (English: $r = -0.33$, $p = 0.10$; Spanish: $r = -0.33$, $p = 0.10$; German: $r = -0.33$, $p = 0.10$), a partial correlation between color hue and letter frequency controlling for letter order (Table 2) can be compared with a partial correlation between color hue and letter order controlling for letter frequency (Table 3).

Table 2. Partial correlations between color hue and letter frequency, controlling for letter order.

	English	Spanish	German
r	0.64	0.44	0.67
p	0.014	0.11	0.012

Table 3. Partial correlations between color hue and letter order, controlling for letter frequency.

	English	Spanish	German
r	0.2769	0.2744	0.2456
p	0.4470	0.4207	0.5470

Lastly, a partial correlation between color hue and letter frequency controlling for both letter order and color term frequency was performed (Table 4). Thus, I can be fairly confident that the correlation between color hue and letter frequency is not due to color term frequency or letter order in the alphabet.

Table 4. Partial correlations between color hue and letter frequency, controlling for color term frequency and letter order.

	English	Spanish	German
r	0.6848	0.3942	0.6251
p	0.0073	0.1674	0.0201

Overall, the data suggests a correlation between color hue and associated letter frequency across all three languages. Within the English language- while the dictionary letter frequencies had the highest correlation value- it is interesting to note that the children's books' letter frequencies had a higher correlation value than the Brown Corpus' letter frequencies. This result parallels the lifelong nature of synesthesia: associations that form in childhood (suggested here to be based on the frequencies of letters within one's childhood) persist unchanged into adulthood. Thus, there is a sort of "critical period" for the formation of synesthetic color associations that I propose is due to the frequency of the letters in the child's native tongue. The stronger correlation from the dictionary rather than children's books is likely due to a simple lack of data- the dictionary's ample amount of sheer data allows the correlation analyses to be far more precise than my assortment of choice children's books.

The partial correlations in the latter portion of this experiment serve to refute the possibility of either color term frequency or letter order influencing the initial correlation between letter frequency and color hue. These two characteristics were areas of concern because a) certain color terms that are more frequent happened to be associated with more frequent letters (ie, red is one of the most common color terms in literature) and b) there is a definite consistency between alphabet letter order and letter frequency, with some of the least frequent letters like X or Z coming at the very end of the alphabet. However, the partial correlation data shows that neither of these factors were the reason that the initial correlation was found.

Overall, the partial correlation data supported the strength of my initial letter frequency-color hue finding. The Spanish partial correlation values were low, but it is important to note that, while the partial correlation between color hue and letter frequency controlling for letter order (Table 2) and the partial correlation between color hue and letter frequency controlling for color term order (Table 1) are not significant, they are far more significant than the partial correlation between color hue and letter order controlling for letter frequency (Table 3). Furthermore, it is interesting to note that the Spanish subject pool was the smallest and least consistent of the three; therefore, the weaker nature of the Spanish correlations is not surprising.

This experiment provided us with the basis of this study: a correlation between letter frequency and color hue that persisted across three languages. I was also able to rule out other avenues of cognitive or environmental influence, such as societal letter order and cultural color term frequency. At last, the synesthetic community can be aware of possible characteristics that are guiding their individual grapheme-color associations.

Next, I tested whether the frequency–hue correlation observed in synesthetes is specific to synesthetic associations, or if it is a general property of semantic associations between letters and colors among all observers. To address this question, I had a group of non-synesthetic participants report the color they most strongly associated with each letter of the English alphabet. If the frequency-hue correlation observed in Experiment 1 is a general property, then the correlation should be observed for this non-synesthetic group as well.

Two hundred and fifty deidentified non-synesthetes were asked to assign a color to each letter of the English alphabet. Many subjects seemed to record color names that began with the letter that they were supposed to be associating with (eg. F is fuchsia, I is indigo); however, others seemed to have other color-letter associations that were not governed by the first letter of the paired color name. In order to discriminate between these two pairing strategies, the number of letters (out of 26) that were associated with colors that began with the same letter ("matching") was counted and recorded individually for each subject. Next, every color name was converted into an RGB value, which was then converted to an HSV value. The color names' assigned RGB values were determined based on the xkcd color name survey, which determined the RGB values of 954 of the most common color names as defined by several hundred thousand participants. The hue of each color name (non-color name words were excluded) was then used to perform the following analyses: average correlation between hue and frequency, standard deviation of correlation, the correlation between the hue-frequency correlation and the number of "matching" (out of 26) color names and letters, and the significance of the correlation between the correlation of hue and frequency and the number of "matching" color names and letters.

The average circular correlation between letter frequency and letter-color among the non-synesthetes was $r = 0.296$. Thus, no significant correlation was found between letter frequencies and color hues for non-synesthetes, even controlling for those subjects who simply named colors that began with the letter with which they were associating.

This suggests that the strong correlation between letter-frequency and associated color hue demonstrated in Experiment 1 is found only in synesthetes, furthering the notion of cognitive experiences and neural mechanisms wholly unique to synesthetes.

In conclusion, I examined whether the colors synesthetes associate with letters are related to the frequency with which those letters appear in text. Specifically, I compared letter frequency to the hues associated with those letters by synesthetes (Experiment 1) and non-synesthetes (Experiment 2). I found a strong correlation between letter-frequency and color hue for synesthetes only. By testing this relationship in multiple languages, which use letters with different frequencies, I were able to demonstrate that this correlation appears to be a frequency effect rather than a letter-shape effect. For example, the letter G is associated with green in English, yellow in Spanish, and Orange in German, and this variability in hue across language is well predicted by the frequency of G in each language (low in English, average in Spanish, and higher in German). These results suggest that the specific hue associated with each letter is highly dependent on experience reading text in one's native language.

Because synesthesia appears to have a strong genetic component (Asher et al., 2009), previous studies have assumed that the colors associated with each letter are genetically determined and specific to each synesthete, even amongst twin pairs (Barnett et al., 2007). Others suggested that color associations are governed by certain interactions in childhood, such as with colored alphabet kitchen magnets (Witthoft & Winawer, 2006). The current results suggest that the colors associated with each letter are affected by the frequency with which the synesthete encounters letters in day to day life, rather than being innate or simply adopted from a single colored alphabet within the home. Presumably the frequency of these letters within the synesthete's native alphabet is a proxy for the frequency of exposure to those letters.

How would the frequency of exposure to letters influence the color associated with that letter? Here, I review the neural mechanisms involved in color and word processing to develop a plausible account of how color–grapheme pairings arise via the interaction of color-processing and word-form processing in the cortex.

Area V4 is located in the extrastriate cortex and appears to play a pivotal role in color perception, as evidenced by neuropsychological and neurophysiological data (Wade et al., 2002). Single cell recording in monkeys have shown that neurons in V4 are clustered in columns by color selectivity (Kotake, 2009). Specifically, color discrimination index values, which compare the firing rates between the most and least preferred colors, are positively correlated between nearby neurons but not between distant neurons, demonstrating that V4 neurons are clustered according their ability to discriminate color (Kotake, 2009). Further, these clusters appear to be organized by long, middle, and short wavelength cone signals (Kotake, 2009), with the majority of V4 neurons preferring red or long-wavelength colors.

Another neural area important to this research is the visual word form area (VWFA), within the temporal lobe of the brain. The VWFA specializes in the process of reading: recognizing, processing, and interpreting both letters and words (Cohen et al., 2004). Additionally, V4 is directly adjacent to the VWFA and has been shown in fMRI studies to be simultaneously activated in synesthetes, suggesting a direct neural cross-activation (Brang et al., 2010, Hubbard et al., 2005).

Taking these features of area V4 and the VWFA into account, my neurophysiological models have proposed that synesthesia is driven by connectivity between the visual word form area and area V4 (reference). Within this framework, the VWFA receives biased inputs with some letters more frequent than others (depending on the language), and area V4 has biased color selectivity with more neurons responding to long-wavelength colors like red (which is presumably independent of language). I propose that these two biases jointly determine which letters and colors become associated in synesthetes. For example, if associations were initially randomly formed between letters and colors, then more frequent letters would form more associations with long-wavelength neurons, and would therefore become associated with red. But this "random association" model would also predict that frequent letters would become associated with other colors, and that less frequent letters would also become strongly associated with red. To explain why that does not occur, I must assume that, as some associations are reinforced through experience, others are inhibited. For instance, as frequent letters become strongly associated with red, their association with other colors must be inhibited, and the association between less frequent letters and red must be inhibited as well. According to this frequency-based-inhibition model, greater letter frequency and greater frequency of color selectivity combine to strongly associate higher frequency letters in word-processing regions (e.g., VWFA) with more prevalent colors in color-processing areas (e.g., V4).

While this account is speculative, it is consistent with known physiology, and provides a possible mechanism for the observed relationship between letter-frequency and letter-hue associations across different languages.

Among English-, Spanish-, and German-speaking synesthetes, the hue associated with a particular letter is correlated with that letter’s frequency in the language. No such correlation between color hue and letter frequency was found in a non-synesthete control population, supporting previous claims that synesthesia is a discrete neurological phenomenon. I propose that synesthetic associations are formed between word processing areas (e.g. VWFA) and color processing areas (e.g., V4), with binding between letters and colors depending jointly on biases in the input (i.e., letter frequency, which varies with language) and biases in color processing (i.e., the uneven distribution of color selectivity within V4, which is independent of language). Though synesthesia has a clear genetic component (reference) and is believed to result from a single-nucleotide polymorphism on the second chromosome (reference), the precise letter-color pairings that are formed as the young synesthete is exposed to letter patterns appears to be based in large part on perceptual experience and the amount of attention each letter receives within the developing brain.

Neurophysiologically, this pattern can be described by the wavelength-specific-color-receptor-neurons of V4 fusing with the language-processing-neurons of the LMTG. The connectivity of V4 and LMTG is supported both topographically (the two regions are near neighbors) and functionally (with V4's colors associating with the LMTG's letter processing). Though synesthesia is genetic, letter-color pairings formed in the young synesthete are based on the amount of attention each letter receives within the developing brain.

Though synesthesia affects a minute portion of the population, research into this neurological phenomenon can have far-reaching benefits. Currently, the most highly supported theory of synesthesia development points to a lack of specific enzymes in early embryonic development. This theory proposes that all fetuses' neurons are completely intertwined, until specific enzymes pare away the excess neuronal connections during development. In synesthetes, these connections remain intact after birth. Accordingly, synesthesia is closely related to conditions like schizophrenia and autism, which similarly involve excess neuronal pathways. For example, autistic children's connections between the visual/auditory regions and the limbic system can cause anger management disabilities sparked by audiovisual cues. If one is interested in researching conditions that involve excess neuron pathways like those listed above, synesthetes are reliable participants as they are not cognitively impaired or taking any inhibiting medications that could disturb the research.

Synesthesia research can also be of significant neurophysiological benefit; studies like this one may use characteristics of synesthesia to learn more about the structure and function of the largely uncharted V4 and middle temporal gyrus. Eventually, it may be possible to induce synesthesia in non-synesthetes to support memory processes by providing sensory aids. This research finally proposes an answer to synesthesia researchers' long- pondered question as well as satiating the curiosity of my own synesthetic mind.

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