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Chai-Youn Kim
Korea University

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Both “나” and “な” are yellow: Cross-linguistic investigation in search of the determinants of synesthetic color

Eun-hye Shin, Chai-Youn Kim*

Department of Psychology, Korea University, Seongbuk-Gu, Anam-ro 145, Seoul 136701, Republic of Korea

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ABSTRACT

Individuals with grapheme-color synesthesia experience “colors” when viewing achromatic letters and digits. Despite the large individual difference in synesthetic association between inducing graphemes and induced colors, the search for the determinants of synesthetic experience has begun. So far, however, research has drawn an inconsistent picture; some studies have shown that graphemes of similar visual shape tend to induce similar synesthetic colors, while others suggested sound as an important factor. Moreover, meaning seems to affect synesthetic color. In the present work, we sought to investigate the determinants of synesthetic color by testing four multilingual grapheme-color synesthetes who experience “colors” upon viewing Korean (hangul), Japanese (katakana and hiragana), and English (Latin alphabet) characters on a standardized color-matching procedure. Results showed that pairs of characters of matched sound tended to induce similar synesthetic colors. This was the case not only between two scripts within the same language (Japanese hiragana and katakana) but also between two different languages (Japanese and Korean). In addition, pairs of characters with similar initial phonemes tended to induce similar colors; this was general across multiple languages. Results also showed that pairs of sequential words in Korean, Japanese, English, and Chinese that have the same meaning tended to elicit similar synesthetic colors. When those pairs of words shared not only meaning but also sound, the similarity of the induced synesthetic colors was even greater. Our work is one of the few initial attempts to examine the influence of visual shape, sound, meaning, and their interaction on synesthetic color induced by characters across multiple languages.

1. Introduction

Synesthesia is a condition under which a stimulus in one sensory modality induces perceptual experience not only in the relevant modality but also in another, ordinarily irrelevant modality (Cytowic and Eagleman, 2009). For example, an individual with auditory–olfactory type synesthesia smells a specific scent when hearing a particular word, while another individual with gustatory–tactile type synesthesia feels a specific shape when having a taste sensation (Cytowic, 1993). Previous research on this beguiling condition has shown that synesthesia can take on various forms, and that the association between the inducing stimulus and induced sensation is idiosyncratic in nature (Jordan, 1917). Both of these make individual differences a key issue in the investigation of synesthesia.

Recent studies on synesthesia, however, have begun to focus on commonalities of associations between the inducing stimulus and induced sensation. Such approaches have been mainly based on grapheme-color synesthesia, one of the most prevalent (Rich et al., 2005; Simner et al., 2006), and most studied types of the condition. In this form of synesthesia, association is not between different modalities but within the same visual modality. People with grapheme-color synesthesia experience vivid and consistent colors when viewing achromatic letters and digits. Despite the wide variety of individual grapheme-color associations, early reports revealed some consistencies. For example, vowel characters tend to induce white or weaker synesthetic colors: “e” and “i” have been found to be associated with yellow or white (Marks, 1975) and “o” is often experienced as white or transparent (Baron-Cohen et al., 1993; Day, 2005; Lay, 1896; but also see Beeli et al., 2007; Smilek et al., 2007). Intrigued by these observations, researchers set out to explore the factors determining synesthetic color in grapheme-color synesthesia.

The search for the determinants of synesthetic color was first attempted by examining large-scale color-matching data sets. For example, Rich and colleagues examined 150 adult lexical-color synesthetes' color-matching results coded in 11 basic categories of color in combination with lightness.[1] They found that the first

* Corresponding author. Tel.: +82 2 3290 2866.
E-mail address: chaikim@korea.ac.kr (C.-Y. Kim).

[1] The eleven color terms include black, white, red, yellow, green, blue, brown, orange, purple, pink, and gray, based on Berlin and Kay (1969).

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letter of the color name tended to induce that color. For a large proportion of the synesthetes tested, "Y" was experienced as yellow and "B" was blue (Rich et al., 2005). Simner and colleagues also tested 70 grapheme-color synesthetes with a questionnaire including a color-matching task, and categorized the reported colors into 11 basic color categories. Their results showed that "A" tended to be experienced as red at a significantly higher level of probability than chance. Upon careful examination, Simner and colleagues found that the frequency of the inducing character seemed to be correlated with the frequency of the names of the induced colors (Simner et al., 2005).

Since the inducing stimuli in grapheme-color synesthesia are linguistic units, other basic linguistic features than frequency including shape (orthography), sound (phonology), and meaning (semantics) were also considered to influence synesthetic color (see Simner (2007) for a review). Results so far, however, do not provide a consistent picture. Some researchers found that graphemes of a similar shape tended to induce similar synesthetic colors (Brang et al., 2011; Rich et al., 2005; Watson et al., 2012). Other researchers emphasized the importance of meaning over shape by showing that a similarly shaped character could take on different synesthetic color based on the semantic context in which it appeared (Dixon et al., 2006; Ramachandran and Hubbard, 2001). For example, "B" induced the color of the digit "13" when it appeared between "12" and "14," whereas the same character induced the color of the letter "B" when it appeared between "A" and "C" (Blake et al., 2005). Furthermore, it was also suggested that graphemes of a similar sound tended to induce similar synesthetic color (Asano and Yokosawa, 2011, 2012).

These seemingly inconsistent results might stem from differences in stimuli and synesthetes tested as well as differences in test procedures and data analysis. Among those various potential sources of inconsistency, we focused on the stimulus aspect here. Brang et al. (2011) suggested that the shape of inducing stimuli was an important factor influencing synesthetic color; they used Latin alphabet characters and single digits as inducing stimuli in the color-matching test. In the studies of Asano and Yokosawa (2011, 2012) where sound was suggested to be important, Japanese characters in three different scripts were used. The choice of Japanese scripts in the latter studies was, as the authors themselves emphasized, based on the shallow orthography (i.e., simple and consistent correspondence between character and sound) of the Japanese language, in contrast to the deep orthography (i.e., complex and inconsistent correspondence between character and sound) found in English. In a more recent work, they also suggested that a Latin alphabet grapheme is different from a Japanese character by having two kinds of phonological information – i.e., its name and its pronunciation, which might weaken the influence of sound on synesthetic colors induced by Latin alphabet grapheme (Asano and Yokosawa, 2013). Asano and Yokosawa suggested that those studies showing the important role of shape over sound in determining synesthetic color might be due to the choice of the particular stimuli (Latin alphabet) and its intrinsic characteristics.

In the current work, we went further from Asano and Yokosawa's suggestion, and explored whether the keen relationship between the sound of the inducing stimulus and the induced synesthetic color found within Japanese scripts can be extended and generalized. We were able to do this because we were fortunate to have access to four multilingual grapheme-color synesthetes who experience colors with Korean, English, Japanese, and some Chinese characters and words as well as digits. Our approach had the following advantages over previous ones. First, it enabled us to explain the factors driving particular grapheme-color pairings within a single individual, with more exemplars. Moreover, this approach enabled us to take into account the linguistic characteristics of multiple languages. The choice of Korean script hangul was critical in particular, since it shares features of Japanese scripts by having shallow orthography whereas it is similar to Latin alphabet in that a hangul grapheme is associated with two kinds of phonological information: the name of the character and how it sounds in a syllable. The latter feature of hangul is retained by hangul consonants. A consonant having its own name (e.g., 'ㄱ (/kiyeok/)' cannot stand alone without being accompanied by a vowel (c-v; e.g., '가(/ka/)') or a vowel plus another consonant (c-v-c; '강(/kang/)'). A syllabary comprising c-v or c-v-c in specific spatial arrangement is a unit character for reading in hangul (Taylor, 1980). Thus, a hangul consonant 'ㄱ' can be associated with different phonemes, though the initial phoneme remains the same. These two characteristics shared by hangul were suggested as what might be behind the discrepancy of previous studies on the determinants of synesthetic color using Latin alphabet and Japanese scripts (Asano and Yokosawa, 2013). Therefore, hangul was expected to provide a clue to estimate the importance of sound as a determinant of synesthetic color.

We are not the first to adapt the cross-linguistic strategy in search of the determinants of synesthetic color. Graphemes of similar shapes, then those of similar sounds were shown to induce similar synesthetic colors across English and modern Greek (Rich et al., 2005) or Cyrillic (Witthoft and Winawer, 2006), both of which suggested visual similarity as a stronger cue than sound similarity. Our study, however, differs from those previous attempts since we examined synesthetic colors associated with characters over four different languages, some of which share more linguistic features (e.g., Korean and Japanese) than others (e.g., Korean and English).

By exploiting the different characteristics of multiple languages, we hoped to elucidate whether any single linguistic feature (e.g., shape, sound, or meaning) outweighs the others or interacts with each other. Specifically, we tested the four multilingual synesthetes with color-matching procedures using (1) Japanese katakana and hiragana, the Korean hangul syllabaries sounds of which match Japanese syllabaries, (2) Korean hangul and English Latin alphabet graphemes, and (3) sequential words, including numbers and weekdays, in Korean, Japanese, English, and Chinese. By utilizing those three classes of stimuli, we predicted (1) that similar synesthetic colors associated with pairs of Japanese and sound-matched Korean syllabaries would extend previous findings from the two Japanese scripts and emphasize the importance of sound in determining synesthetic color. If this would be the case, we also predicted (2) that syllabaries and graphemes, with only initial phonemes shared, would induce similar synesthetic colors, but the degree of induced color similarity might follow the degree of sound similarity. We also predicted (3) that sequential words with the same meaning over multiple languages would induce similar synesthetic colors, and the impact of meaning and sound would be additive. Last but not least, we re-examined the three predictions above with a data-driven approach comparing the degrees of influence of shape, sound, and meaning on synesthetic color. Results from these tests and analyses are described below.

2. Methods

2.1. Participants

Four Korean grapheme-color synesthetes (3 females, 21–27 years of age) participated in the study. All four synesthetes reported "seeing" colors in their mind's eye when viewing individual graphemes, syllabaries, and words, and were, therefore, classified as *associators* (Dixon et al., 2004). Moreover, our participants were multilingual synesthetes who experienced synesthetic colors when viewing not only Korean but also English, Japanese, and Chinese characters and words. Three of the four participants reported differences in the strength of synesthetic colors elicited by the different languages. For example, SKK reported experiencing stronger synesthetic colors upon viewing graphemes and words in Korean and English than upon viewing them in Japanese. However, we found no obvious

Table 1
Information regarding synesthesia-inducing languages and relative vividness of induced synesthetic colors experienced by the four multilingual synesthetes who participated in the current study.

Synesthete	Language	Fluency (1: not fluent at all, 5: very fluent)				Age Acquired	Frequency of Use	Residence in Countries Using the Language	Vividness of Synesthetic Color (Rank Order)
		Listening	Reading	Speaking	Writing				
HUP	Korean	5	5	5	5	Before 3	Everyday	Over 20 years	3
	Japanese	1	2	1	1	15–19	Rarely	–	2
	English	2	3	2	2	4–8	Once a month	–	1
KBL	Korean	5	5	5	5	Before 3	Everyday	Over 20 years	3
	Japanese	5	5	5	5	4–8	Everyday	1–10 years	2
	English	3	5	3	4	Before 3	Everyday	1–10 years	1
SKK	Korean	5	5	5	5	Before 3	Everyday	Over 20 years	1
	Japanese	3	2	2	2	15–19	Rarely	–	2
	English	4	5	3	4	4–8	Three times a week	1–10 years	1
YMK	Korean	5	5	5	5	Before 3	Everyday	Over 20 years	1
	Japanese	1	1	1	1	After 20	Rarely	− 1 year	1
	English	3	3	2	3	9–14	Three times a week	− 1 year	1

correlation between the strength of synesthetic color experience and acquisition time, years of use, or fluency of the synesthete in each language (see Table 1 for details).

2.2. Stimuli

A total of 174 synesthesia-inducing graphemes and syllabaries were used for the synesthetic color-matching test (90 Japanese graphemes [45 hiragana and 45 katakana, which are also syllabaries]; 44 hangul syllabaries, each of which was composed of two graphemes including a consonant and a vowel matching the sound of Japanese graphemes; 14 hangul consonants; and 26 Latin alphabet graphemes). In addition, a total of 64 sequential words were used: 9 numbers (i.e., 1–9) and 7 weekdays (i.e., Monday–Sunday) in four languages (Korean, Japanese, English, and Chinese). Nine Arabic digits were also included. All stimuli were presented in black against a gray background. Each stimulus was shown in Arial font; the scale of the stimuli bore slight discrepancies between languages due to differences in composition and shape. Japanese graphemes subtended $1.57^{\circ} \times 1.85^{\circ}$ in visual angle, hangul syllabaries $2.14^{\circ} \times 2.14^{\circ}$, hangul consonants $1.99^{\circ} \times 1^{\circ}$, Lain alphabet graphemes $1.57^{\circ} \times 2.14^{\circ}$, and Arabic digits $.9^{\circ} \times 1.99^{\circ}$, on average.

2.3. Apparatus

Stimuli were presented on a 19-in. color-calibrated CRT monitor (1024×768 resolution, 60 Hz frame rate) controlled by an Intel PC using Matlab 7.0.4 (Math-Works, 2005) and the Psychophysics Toolbox 2.54 (Brainard, 1997; Pelli, 1997). Testing was conducted in a quiet, dark room in which the video monitor provided the only source of illumination.

2.4. Procedure

To match the synesthetic colors of graphemes, syllabaries, and sequential words, we used a modified version of the standardized Synesthesia Battery (Eagleman et al., 2007). The test comprised five blocks: (1) hiragana, (2) katakana, (3) hangul syllabaries, (4) hangul and Latin alphabet graphemes, and (5) sequential words and digits. The order of the blocks was pseudo-randomized between participants. In each block, stimuli were presented three times in a pseudo-randomized order. In each trial, the inducing stimulus and color palette were presented simultaneously. Participants were instructed to click on the color in the palette that corresponded to the synesthetic color induced by the stimulus using a mouse. Then, they were asked to use the two keys on the keyboard to match the brightness of the experienced synesthetic color: the "←" key to decrease or the "→" key to increase the brightness. There was a "no color" button at the bottom of the color palette for such cases as synesthetic color was not induced by a given stimulus.

2.5. Data analysis

A consistency score based on the color-matching results was computed for each stimulus (Eagleman et al., 2007). Stimuli for which the consistency score was lower than 1 were selected for further analysis.[2] Matched colors for each inducing stimulus for three times were averaged and converted to CIE *xy*Y color coordinates.[3] For the Japanese and Korean syllabaries, pairs of stimuli with matched sounds were first selected and classified into three subgroups: the pairs of hiragana and katakana, pairs of hangul and hiragana, and pairs of hangul and katakana. In addition, those Japanese and Korean syllabaries were paired with Latin alphabets and hangul consonants with similar initial phonemes. Next, a color variation index (CVI) was calculated to compare the Euclidean distance between the pairs of matched colors induced by the pairs of stimuli in the color space (Asano and Yokosawa, 2011).[4] The mathematical formula for computing the CVI was as follows:

$$\text{CVI}\ (a,b) = \sqrt{(x\_b - x\_a)^2 + (y\_b - y\_a)^2}$$

where a and b are the matched colors of a pair of inducing stimuli, whose coordinates on the CIE *xy*Y are (x_a, y_a) and (x_b, y_b) respectively.

Due to the large differences in the number of character pairs of similar sounds and those of dissimilar sounds, it was not plausible to compare them directly. Therefore, we chose to compare the mean CVI for each subgroup of pairs of sound-matching stimuli with the baseline CVI. To determine the baseline values, the group mean CVI was computed for each synesthete based on all possible pairs of matched colors for all the graphemes and syllabaries. A mean CVI smaller than baseline for a subgroup, verified by one-sample t-test, indicates that the matched colors for the pairs of stimuli in that subgroup are located in the color space more closely than those for all possible pairs. p-Values of the multiple mean CVIs of a comparison were adjusted using the false discovery rate (FDR, Benjamini and Hochberg, 1995) method in consideration of the problem of multiple comparison. FDR correction was applied once for all 10 comparisons for the Japanese and Korean syllabaries, and separately for all 22 comparisons for the syllabaries and initial phone-matched consonants.

For the sequential words, pairs of synonyms were first selected and classified into two subgroups: pairs of words with the same meaning and similar sounds, or pairs of words with the same meaning but dissimilar sounds. The group mean CVI was computed based on all possible pairs of matched colors for all the sequential words to serve as a baseline. This baseline was compared with the mean CVIs for the two subgroups. p-Values of the multiple mean CVIs of a comparison were adjusted using the FDR method in consideration of the problem of multiple comparison. FDR correction was applied to all 24 comparisons at once.

In addition, we employed a clustering method for a data-driven approach. Based on the CIE *xy*Y coordinates of all the matched colors, we created a two-dimensional

[2] The average consistency score over the inducing stimuli, if less than 1, is generally considered as an indicator for the reliable synesthetic color experience (Eagleman et al., 2007). However, this method has been questioned as being too conservative (Rothen et al., 2013). Therefore, in an additional analysis, we included all the means of the matched colors without screening them based on the consistency scores. The results were identical to the current ones even with all the matched colors included in the analysis.

[3] Results were identical when using the second one of the three matched colors, not the average of them, for each inducing stimulus.

[4] Note that our choice of color space (CIE xyY) was different from that by the previous study (CIE Lab), so the resulting CVIs were in different ranges.

histogram of the matched colors for all the stimuli. All the mean matched colors from three different measures – even the same colors matched with multiple different characters (though not often the case) – were included in the analysis. The histogram was created using narrow bins (50 × 50) and additional smoothing. The smoothing of the two-dimensional histogram was based on an algorithm by Eilers and Goeman (2004) using penalized likelihood estimation (Eilers and Goeman, 2004). The 50 × 50 matrix A of counts of characters on the *xy*Y color space was converted into another 50 × 50 matrix B using the following smoothing function: $B=(I+\lambda^2D2'D2+2\lambda D1'D1)/A$ where I is the identity matrix, $D1$ is the matrix of row differences for I, and $D2$ is the 2nd order difference along the first non-singleton dimension. The smoothing parameter λ was set to .5 to retain the raw data (higher values lead to greater smoothing whereas values close to 0 lead to a plot that is essentially just the raw data; see Eilers and Goeman, 2004). As an output of the algorithm, density values were generated for each bin. The range of density values was between 0 (no inducing characters) and 1 (many inducing characters). To identify a limited number of prominent clusters, we defined a group of five or more consecutive bins with density values larger than .7 as our cluster, which removed all the small clusters leaving a few greatest clusters. We then inspected characteristics of the stimuli within the clusters.

3. Results

3.1. Results from CVI analysis

3.1.1. Japanese (hiragana and katakana) and Korean (hangul) syllabaries: the effect of sound

The color-matching results for the Japanese and sound-matched Korean syllabaries are shown in Fig. 1. In the figure, each row shows the synesthetic colors for the Japanese and Korean characters of matched sound for the four participants. The results showed that the stimuli of matched sounds tended to induce similar colors. For example, "나" and "な" are pronounced as /na/ and induce similar shades of yellow for YMK.[5]

CVI analysis statistically confirmed this observed tendency (Fig. 2). For all four synesthetes tested, CVIs for most subgroups of matched-sound pairs were smaller than the group mean baseline CVI (.1233, SD=.0847; see Fig. 2A), implying that syllabaries of matched sounds are closer together in the color space. Specifically, CVIs for the pairs of hiragana and katakana were statistically different from the baseline in all but only one of the four synesthetes, replicating the previous results of Asano and Yokosawa in synesthetes whose first language is not Japanese.[6] Moreover, CVIs for both the pairs of hiragana and hangul and the pairs of katakana and hangul showed the same pattern of results. These results extend the importance of sound in determining synesthetic color and imply that syllabaries of matched sounds over multiple languages tend to induce similar synesthetic color. Statistical details are shown in Table 2.

In a further analysis, we compared individual CVIs for three subgroups of pairs with matched sounds with the mean CVI for each individual synesthete rather than using the group mean CVI as a baseline. This was done because the synesthetes' "color palettes" showed large individual differences. For example, SKK's "colors" for the inducing stimuli are mostly soft and pale. As a result, her CVIs were smaller on average and less variable than those of the other three synesthetes. In contrast, KBL experiences "primary colors"; his CVIs were larger on average and more variable than those of the other three (see Fig. 1). Mean CVIs for each synesthete were as follows: HUP: .1254 (SD=.0883), KBL: .1434 (SD=.093), SKK: .0874 (SD=.0583), and YMK: .1201 (SD=.0607). When compared with individual baselines, results were identical to those compared with the group mean baseline (Fig. 2B). Namely, syllabaries of matched sounds are closer together in the color space, implying that they induce similar synesthetic colors. Therefore, we used the group mean baseline CVI for the rest of the CVI analysis.

3.1.2. Adding Korean (hangul) and English (Latin alphabet) graphemes to Japanese and Korean syllabaries: the effect of the initial phoneme

To examine the role of initial phonemes in determining synesthetic colors, Korean and English graphemes were added to the Japanese and Korean syllabaries. Specifically, we selected hangul and Latin alphabet graphemes with phonemes similar to the initial phonemes of the hiragana, katakana, and matched hangul syllabaries. The results are shown in Fig. 3.

With those added color-matching results, we were able to compare the degree of similarity of synesthetic colors induced by within- and between-language characters with matched initial phonemes. Overall, syllabaries and graphemes with matched initial phonemes tended to induce similar synesthetic colors. This is indicated by the tendency of CVIs for most subgroups of pairs with matched initial phonemes to be smaller than the group mean baseline CVI.

Interestingly, this tendency was most obvious in CVIs for the pairs of Korean syllabaries and Korean graphemes. The CVIs for the pairs of hangul syllabaries and initial-phoneme-matched hangul consonants differed from the group mean baseline (.1295, SD=.0836) in the greatest magnitude. This difference was statistically significant in all four synesthetes. In addition, it was more obvious in CVIs for the pairs of Japanese syllabaries and Korean graphemes compared to English graphemes. For all four synesthetes tested, CVIs for the pairs of Japanese syllabaries and initial-phoneme-matched hangul graphemes were smaller than the group mean baseline. Specifically, CVIs for the pairs of hiragana and hangul graphemes were significantly different from the baseline in three of the four synesthetes. CVIs for the pairs of katakana and hangul graphemes showed the same pattern of results. These results suggest that Japanese/Korean syllabaries and initial-phoneme matched Korean graphemes are closer together in the color space, implying that they induce similar synesthetic colors. In contrast, when paired with initial-phoneme-matched Latin alphabet graphemes, Japanese and Korean syllabaries showed CVIs indistinguishable from the mean baseline CVI in several cases. Specifically, CVIs for the pairs of hiragana and initial-phoneme-matched Latin alphabet graphemes differed from the baseline in only half of the synesthetes tested. CVIs for the pairs of Korean syllabaries and initial-phoneme-matched Latin alphabet graphemes showed the same pattern of results. In addition, CVIs for the pairs of katakana and initial-phoneme-matched Latin alphabet graphemes differed from the baseline in only two out of three synesthetes. These results suggest that the degree of synesthetic color similarity differs between initial-phoneme-matched characters within the same language and those across different languages. They also suggest that Japanese/Korean syllabaries and initial-phoneme matched Latin alphabet graphemes do not tend to induce synesthetic colors as similar as do initial-phoneme matched Korean graphemes. Statistical details are shown in Table 3.

3.1.3. Sequential words in four languages: the effect of meaning

The color-matching results for the sequential words in four languages (as well as Arabic numerals for the numbers) are shown in Fig. 4. Each row shows the synesthetic colors for numbers and weekdays across different linguistic forms with the same meaning for two synesthetes. These results show that synonyms tended to induce similar synesthetic colors.

CVI analysis statistically confirmed this observed tendency (Fig. 5). The group mean baseline CVIs for numbers and weekdays were computed separately (numbers: .1473, SD=.0934;

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[5] Fig. 1 shows that most characters of which the initial phoneme is /n/ induced shades of yellow for all four synesthetes. Interestingly, as previously reported, the Korean word for yellow sounds like /norang/; thus, the first letter of the color name induced that color (Rich et al., 2005).

[6] One of the four participants, YMK, did not experience any synesthetic colors when viewing katakana characters.

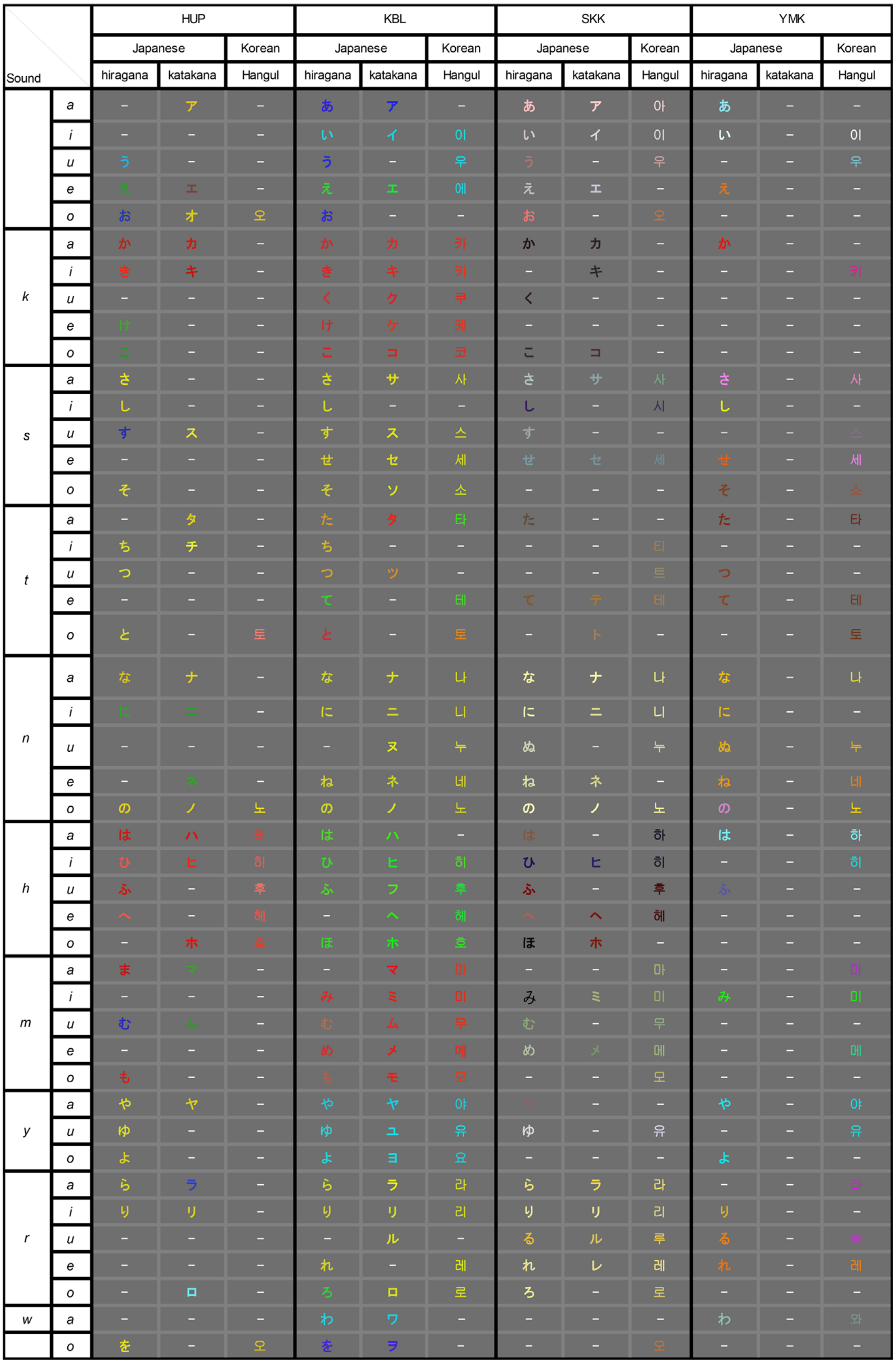


Fig. 1. Color-matching results (averaged from three measures for each character) from the four synesthetes for Japanese hiragana, katakana, and sound-matched Korean Hangul syllabaries. "–" indicates that (1) no synesthetic color is experienced or that (2) the consistency score was higher than 1 and thus excluded from further analysis.

weekdays: .1376, SD=.0884). For all four synesthetes tested, CVIs for pairs of sequential words with the same meaning were smaller than the group mean baseline CVI (see Fig. 5A). Specifically, individual CVIs for pairs of number synonyms were different statistically from the group mean baseline in all four participants. In addition, CVIs for pairs of weekday synonyms were different statistically from the group mean baseline in three out of four synesthetes.

To examine whether the influence of sound and meaning on synesthetic color is additive, we conducted an additional analysis by categorizing the pairs of synonyms into two subgroups according to their similarity of sound (see Fig. 5B). For numbers, individual CVIs for pairs of words with the same meaning and similar sound were different statistically from the group mean baseline in all four synesthetes. Individual CVIs for word pairs with the same meaning but dissimilar sound were significantly smaller than the group mean baseline in three of the four synesthetes. Statistical details are shown in Table 4. For weekdays, CVIs for pairs of words with the same meaning and similar sound were significantly smaller than the group mean baseline in all four synesthetes. CVIs for the pairs of words with the same meaning but dissimilar sound were

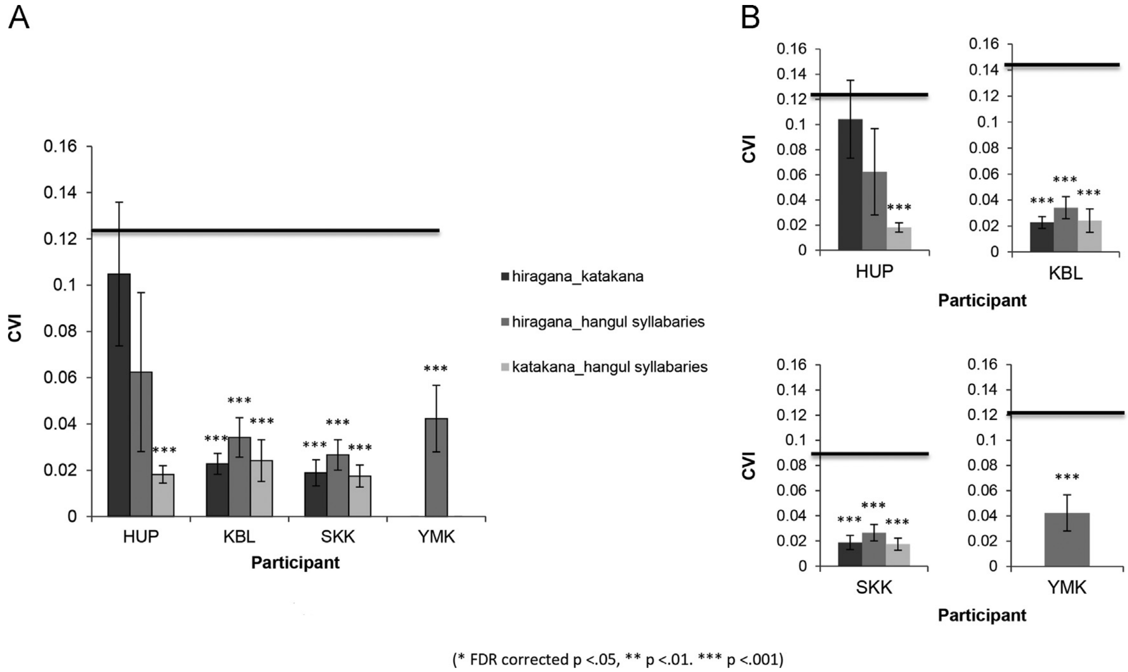


Fig. 2. Color variation indices (CVIs) for the two types of Japanese (hiragana and katakana) and sound-matched Korean hangul syllabaries. The horizontal solid line in each panel indicates the baseline CVI. (A) Comparison of CVIs for the pairs of three subgroups with the group mean baseline CVI. (B) Comparison of CVIs for the pairs of three subgroups with each individual mean baseline CVI (*** $p < .001$, *corrected*).

Table 2
Statistical information regarding pairs of colour variation indices (CVIs) for the two types of Japanese (hiragana and katakana) and sound-matched Korean hangul syllabaries. Descriptive statistics including the means and standard deviations and results from the one-sample *t* test are shown for each pair for each synesthete.

Synesthete	Pairs	Mean	Standard deviation	*t*	df	*p* Value	Cohen's *d*
HUP	Hiragana–katakana	.104	.124	−.618	15	.546	−.154
	Hiragana–hangul syllabaries	.062	.097	−1.773	7	.120	−.627
	Katakana–hangul syllabaries	.018	.008	−28.133	4	.000	−12.581
KBL	Hiragana–katakana	.023	.026	−22.269	33	.000	−3.820
	Hiragana–hangul syllabaries	.034	.049	−10.526	32	.000	−1.832
	Katakana–hangul syllabaries	.024	.051	−11.016	31	.000	−1.947
SKK	Hiragana–katakana	.019	.026	−18.651	20	.000	−4.070
	Hiragana–hangul syllabaries	.027	.033	−14.683	24	.000	−2.937
	Katakana–hangul syllabaries	.018	.019	−21.992	15	.000	−5.498
YMK	Hiragana–hangul syllabaries	.042	.058	−5.633	15	.000	−1.408

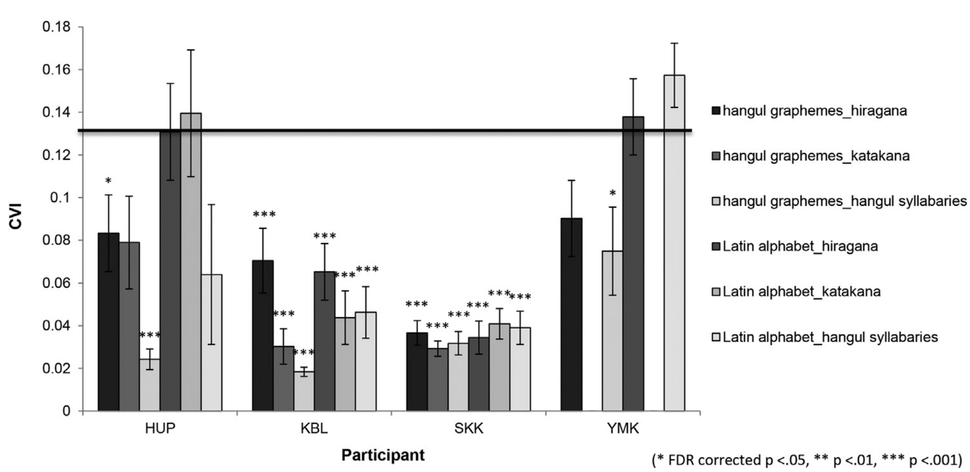


Fig. 3. CVIs for the Japanese and Korean syllabaries, compared to the Korean and English graphemes of which the initial phonemes were matched. The horizontal solid line in each panel indicates the group mean baseline CVI (* $p < .05$, and *** $p < .001$, *corrected*).

Table 3
Statistical information regarding pairs of CVIs for the two types of Japanese (hiragana and katakana) and sound-matched Korean hangul syllabaries and initial phoneme-matched hangul or Latin alphabet characters. Descriptive statistics including the means and standard deviations and results from the one-sample *t* test are shown for each pair for each synesthete.

Synesthete	Pairs	Mean	Standard deviation	*t*	df	*p* Value	Cohen's *d*
HUP	Hangul graphemes–hiragana	.083	.068	−2.574	13	.023	−.688
	Hangul graphemes–katakana	.079	.072	−2.328	10	.042	−.702
	Hangul graphemes–hangul syllabaries	.024	.012	−21.813	5	.000	−8.905
	Latin alphabet–hiragana	.131	.109	.058	22	.954	.012
	Latin alphabet–katakana	.140	.111	.336	13	.742	.090
	Latin alphabet–hangul syllabaries	.064	.094	−1.835	6	.116	−.694
KBL	Hangul graphemes–hiragana	.070	.086	−3.899	31	.000	−.689
	Hangul graphemes–katakana	.030	.046	−11.930	30	.000	−2.142
	Hangul graphemes–hangul syllabaries	.018	.012	−50.636	27	.000	−9.569
	Latin alphabet–hiragana	.065	.054	−4.867	16	.000	−1.181
	Latin alphabet–katakana	.044	.056	−6.818	19	.000	−1.525
	Latin alphabet–hangul syllabaries	.046	.053	−6.890	18	.000	−1.581
SKK	Hangul grapheme–hiragana	.064	.030	−16.043	25	.000	−3.146
	Hangul grapheme–katakana	.029	.015	−28.298	15	.000	−6.863
	Hangul grapheme–hangul syllabaries	.024	.012	−17.707	24	.000	−3.541
	Latin alphabet–hiragana	.034	.032	−12.211	16	.000	−2.962
	Latin alphabet–katakana	.041	.026	−12.452	12	.000	−3.454
	Latin alphabet–hangul syllabaries	.039	.030	−11.636	14	.000	−3.004
YMK	Hangul grapheme–hiragana	.090	.071	−2.202	15	.044	−.550
	Hangul grapheme–hangul syllabaries	.075	.074	−2.646	12	.021	−.734
	Latin alphabet–hiragana	.138	.064	.467	12	.649	.129
	Latin alphabet–hangul syllabaries	.157	.056	1.852	13	.087	.495

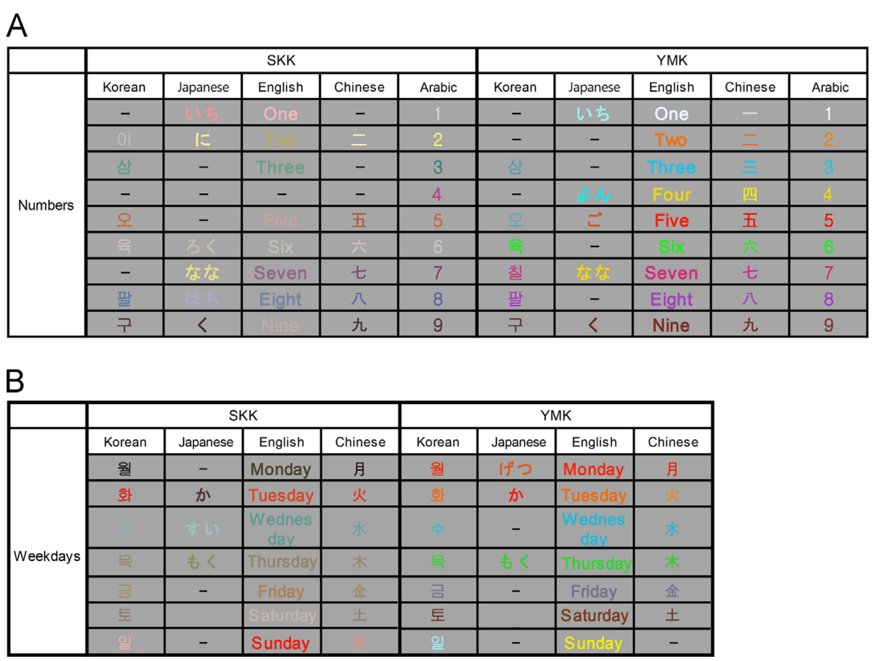


Fig. 4. Color-matching results (averaged from three measures for each word) from the two synesthetes for sequential words in various forms: Korean, Japanese, English, Chinese, and Arabic numerals. "–" indicates that (1) no synesthetic color is experienced or (2) the consistency score was higher than 1 and thus excluded from further analysis.

significantly smaller than the group mean baseline in three of the four synesthetes. Taken together, these results imply that synonyms tend to induce similar synesthetic colors and this tendency is more apparent when they share phonetic similarity as well. Statistical details are shown in Table 5.

3.2. *Results from the clustering analysis*

3.2.1. *Graphemes and syllabaries*

For the four synesthetes tested, different numbers of clusters were identified among the matched colors on the CIE *xyY* color space for the graphemes and syllabaries; 3 for HUP, 4 for KBL, 1 for SKK, and 4 for YMK (Fig. 6A). Within those identified clusters, there were more graphemes and syllabaries with similar sounds than graphemes and syllabaries with similar shapes in all four synesthetes. Specifically for KBL, 91 graphemes and syllabaries with matched sounds were within four clusters (*cluster* 1: 2 for /ma/, 3 for /mi/, 2 for /mu/, 2 for /me/, 2 for /mo/, 3 for /ka/, 3 for /ki/, 3 for /ku/, 3 for /ke/, 2 for /ko/; *cluster* 2: 3 for /na/, 2 for /ni/, 2 for /nu/, 3 for /ne/, 3 for /no/, 3 for /sa/, 3 for /su/, 3 for /se/, 3 for /so/, 3 for /ra/, 3 for /ri/; *cluster* 3: 2 for /h/, 2 for /ha/, 3 for /hi/, 3 for /hu/, 2 for /he/, 3 for /ho/, 2 for /te/, 3 for /e/; and *cluster* 4: 3 for /i/, 3 for /ya/,

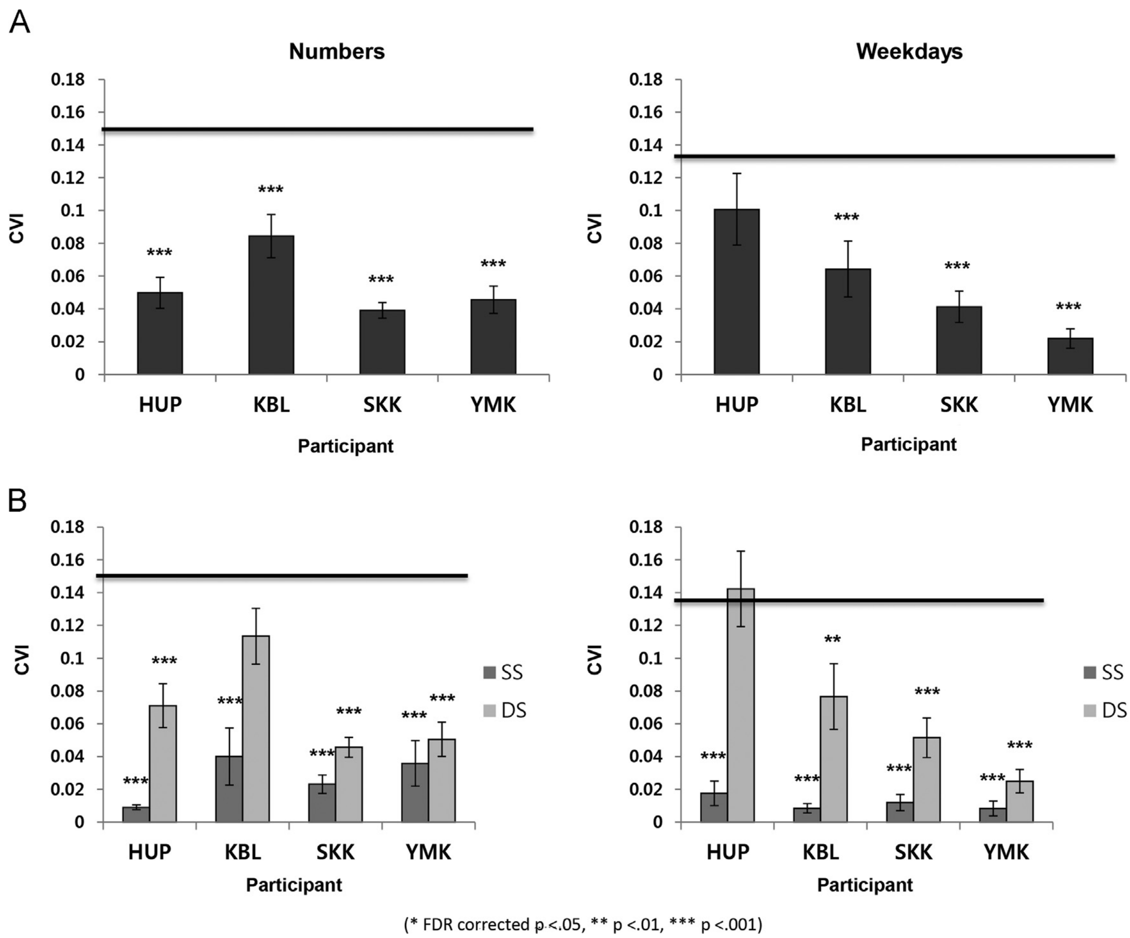


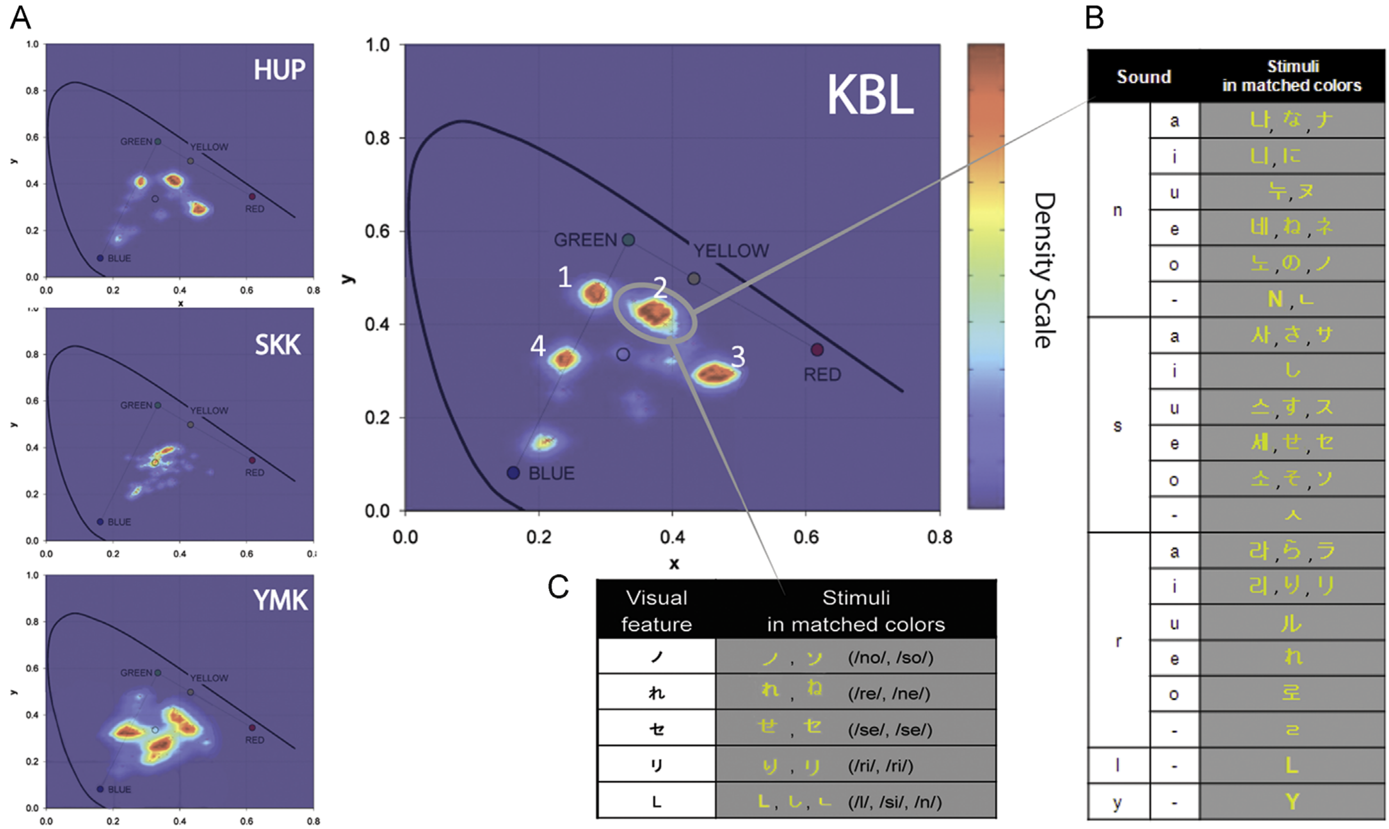
Fig. 5. CVIs for the sequential words. (A) CVIs for the pairs of synonyms in various linguistic forms. (B) CVIs for the pairs of synonyms in the two subgroups (SS: similar sound, DS: dissimilar sound); numbers (left) and weekdays (right). The horizontal solid line in each panel indicates the group mean baseline CVI (** $p<01$, and *** $p<.001$, *corrected*).

Table 4
Statistical information regarding pairs of CVIs for number words of the same meanings with or without similarity in sound. Descriptive statistics including the means and standard deviations and results from the one-sample *t* test are shown for each pair for each synesthete.

Synesthete	Pairs (numbers)		Mean		Standard deviation		*t*		df		*p* Value		Cohen's *d*	
HUP	Same meaning	+Similar sound	.050	.010	.078	.007	−10.260	−96.190	66	22	.000	.000	−1.253	−20.057
		+Dissimilar sound		.071		.089		−5.683		43		.000		−.857
KBL	Same meaning	+Similar sound	.084	.040	.096	.080	−4.759	−6.160	52	20	.000	.000	−.654	−1.344
		+Dissimilar sound		.114		.096		−1.992		31		.055		−.352
SKK	Same meaning	+Similar sound	.040	.023	.036	.023	−22.779	−21.873	57	16	.000	.000	−2.991	−5.305
		+Dissimilar sound		.046		.039		−16.833		40		.000		−2.629
YMK	Same meaning	+Similar sound	.046	.036	.067	.064	−12.213	−7.981	62	20	.000	.000	−1.539	−1.742
		+Dissimilar sound		.051		.067		−9.317		41		.000		−1.438

Table 5
Statistical information regarding pairs of CVIs for weekday words of the same meanings with or without similarity in sound. Descriptive statistics including the means and standard deviations and results from the one-sample *t* test are shown for each pair for each synesthete.

Synesthete	Pairs (weekdays)		Mean		Standard deviation		*t*		df		*p* Value		Cohen's *d*	
HUP	Same meaning	+Similar sound	.101	.018	.085	.017	−1.683	−16.097	14	4	.115	.000	−.435	−7.199
		+Dissimilar sound		.142		.073		.202		9		.844		.064
KBL	Same meaning	+Similar sound	.064	.008	.098	.007	−4.315	−45.981	32	5	.000	.000	−.751	−18.772
		+Dissimilar sound		.077		.104		−3.040		26		.005		−.585
SKK	Same meaning	+Similar sound	.041	.011	.050	.011	−10.095	−29.640	26	6	.000	.000	−1.943	−11.203
		+Dissimilar sound		.052		.054		−7.154		19		.000		−1.600
YMK	Same meaning	+Similar sound	.022	.008	.030	.010	−19.454	−28.620	26	4	.000	.000	−3.744	−12.799
		+Dissimilar sound		.025		.033		−15.862		21		.000		−3.382



Sound		Stimuli in matched colors
n	a	나, な, ナ
	i	니, に
	u	누, ヌ
	e	네, ね, ネ
	o	노, の, ノ
	-	N, ㄴ
s	a	사, さ, サ
	i	し
	u	스, す, ス
	e	세, せ, セ
	o	소, そ, ソ
	-	ㅅ
r	a	라, ら, ラ
	i	리, り, リ
	u	ル
	e	れ
	o	로
	-	ㄹ
l	-	L
y	-	Y

Visual feature	Stimuli in matched colors
ノ	ノ, ソ (/no/, /so/)
れ	れ, ね (/re/, /ne/)
セ	せ, セ (/se/, /se/)
り	り, リ (/ri/, /ri/)
L	L, し, ㄴ (/l/, /si/, /n/)

Fig. 6. Results from the clustering analysis of the matched colors on the CIE *xy*Y color space for graphemes and syllabaries. (A) Heat map results of the "colors" induced by graphemes and syllabaries for all four synesthetes. *X* and *Y* axes correspond to CIE *x* and *y*, respectively. The color bar indicates density values for each bin ranging from blue (0) to red (1). (B) Inducing stimuli within KBL's cluster 2 are sorted based on sound and shown in matched colors. (C) Inducing stimuli with similar visual features in within KBL's cluster 2. The lefthand column shows visual features shared by the stimuli in the righthand column. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4 for /yu/, 3 for /yo/, 2 for /wa/), whereas only 17 graphemes and syllabaries with similar shapes (without similar initial phoneme) were observed (*cluster* 1: 3 for "ㄱ", 3 for "ク"; *cluster* 2: 2 for "ノ", 3 for "L", 2 for "れ"; *cluster* 3: 2 for "は", 2 for "へ"). Fig. 6 shows the clustering results of KBL. The other three synesthetes also showed the same trend; HUP: 32 stimuli with matched sounds, 19 with similar shapes; SKK: 15 stimuli with matched sounds, 2 with similar shapes; YMK: 20 stimuli with matched sounds, 6 with similar shapes. For details, see Supplementary Tables S1 and S2. Furthermore, even more stimuli with similar sounds were observed within the identified clusters if the sound similarity was extended to initial phonemes: HUP, 59; KBL, 107; SKK, 16; YMK, 43 (Supplementary Table S1 for more details). These results suggest that characters that are clustered together on the color space (i.e., inducing similar synesthetic colors) tend to share similar phonetic features.

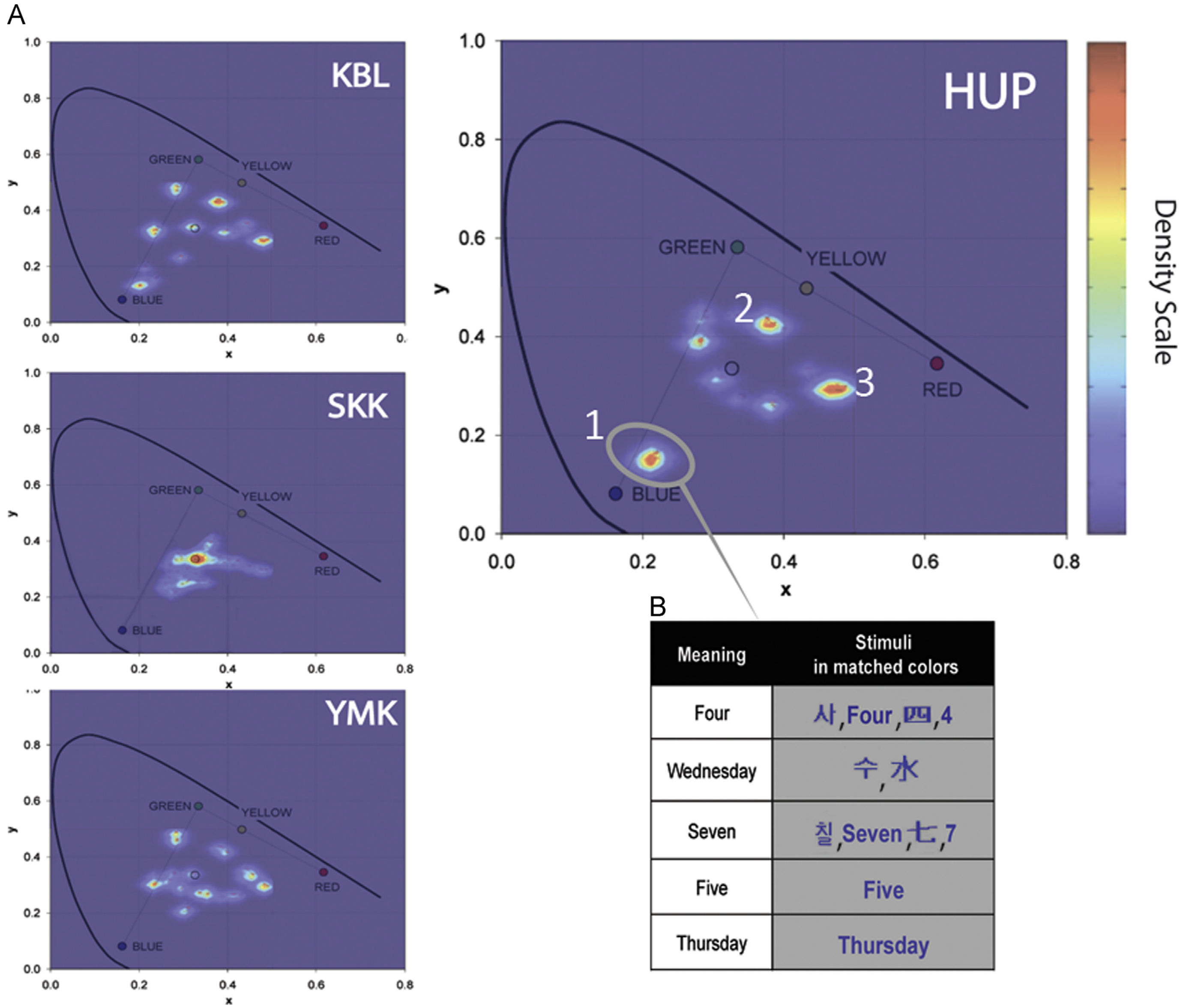
3.2.2. Sequential words

For the four synesthetes tested, different numbers of clusters were identified among the matched colors on the CIE *xy*Y color space for sequential words; 3 for HUP, 2 for KBL, 1 for SKK, and 2 for YMK (Fig. 7A). Within those identified clusters, all four synesthetes showed more words with meanings identical to the other words in the same cluster than not. For HUP in particular, 30 out of 36 words total in the 3 clusters were classified as synonyms; cluster 1: 4 for "four", 2 for "wednesday", 4 for "seven"; cluster 2: 3 for "five", 2 for "friday", 3 for "three", cluster 3: 3 for "one", 3 for "tuesday", 2 for "saturday", 4 for "six". Fig. 7 shows the clustering results from HUP. The other three synesthetes also showed the same trend; YMK: 12 synonyms (for 4 meanings) out of 13; KBL: 12 synonyms (for 4 meanings) out of 15; SKK: 14 synonyms (for 4 meanings) out of 18.

The words with the same meanings were then categorized into two subgroups to examine the relationship between the influence of meaning and sound in determining synesthetic colors induced by those sequential words. The results showed that there were more synonyms with similar sounds than synonyms with dissimilar sounds in the clusters of the three out of the four synesthetes; YMK: 8 synonyms with similar sounds out of 12 (cluster 1: 2 for "wednesday /su/," 2 for "three /sam/," and cluster 2: 2 for "monday /wol/," 2 for "five /o/"); HUP: 24 synonyms with similar sounds out of 30; KBL: 6 synonyms with similar sounds out of 12; SKK: 9 synonyms with similar sounds out of 14. For more details, see Supplementary Table S2.

4. Discussion

Our examination of the synesthetic color experiences of four multilingual synesthetes revealed that characters of matched sound between Korean, Japanese, and English syllabaries and graphemes tended to induce similar synesthetic colors. Moreover, characters across different languages with similar initial phonemes also tended to induce similar synesthetic colors. We further demonstrated that sequential words in Korean, Japanese, English, and Chinese with the same meaning tended to induce similar synesthetic colors. In summary, sound seems to be a major factor in determining synesthetic colors of graphemes and syllabaries, while meaning seems to be an important factor in determining synesthetic colors of sequential words.



Meaning	Stimuli in matched colors
Four	사,Four,四,4
Wednesday	수,水
Seven	칠,Seven,七,7
Five	Five
Thursday	Thursday

Fig. 7. Results from the clustering analysis of the matched colors on the CIE *xy*Y color space for sequential words. (A) Heat map results of the "colors" induced by sequential words for all four synesthetes. (B) Inducing stimuli within HUP's Cluster 1 are sorted based on meaning and shown in matched colors. The lefthand column shows the meaning of the stimuli in the righthand column. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As is generally the case for literature on grapheme-color synesthesia, the search for the determinants of synesthetic color has been pursued mostly by testing synesthetes whose first language is English. Only a handful of studies have been conducted on grapheme-color synesthetes who experience colors with non-English languages such as German (Emrich et al., 2004), Hebrew (Cohen-Kadosh et al., 2007), Korean (Kim and Kim, 2009), and Chinese (Hung, 2013; Hung et al., 2013; Simner et al., 2011). There are also few studies of English-speaking grapheme-color synesthetes who also experience colors with characters of multiple different languages such as Irish Gaelic, French, German, Italian (Barnett et al., 2009), Greek (Rich et al., 2005), Russian (Mills et al., 2002; Witthoft and Winawer, 2006), and Chinese (Hung, 2013; Ramachandran and Hubbard, 2003). Moreover, most of those studies were based on anecdotal observations or case reports. The current work provides one of few initial analyses of the determinants of synesthetic color based on a systematic examination of multilingual grapheme-color synesthetes who experience colors with characters of their first language (i.e., Korean), English, and languages other than English (i.e., Japanese and Chinese) as well.

This last aspect was indeed very useful, since it provided us an unusual opportunity to exploit cross-linguistic comparisons in the synesthetic color-matching data. Our results showed the importance of the initial phonemes in determining the synesthetic colors of graphemes and syllabaries within a language and across different languages (Fig. 3). Interestingly, individual CVIs for the pairs of Korean syllabaries and graphemes that shared initial phonemes were the smallest of the 6 subgroups of pairs, suggesting that characters within (the first) language induced more similar colors than those across different languages. Moreover, CVIs for the pairs of initial-phoneme-matched Korean graphemes and Japanese syllabaries were smaller than those of the English graphemes and Japanese syllabaries. This cannot be due to developmental psycholinguistic reasons such as acquisition time (Mroczko-Wąsowicz and Nikolić, 2013) or fluency (Rich et al., 2005) as proposed in previous studies. The two synesthetes who showed smaller CVIs for the pairs of Korean/Japanese syllabaries than for the pairs of Korean/Latin graphemes (i.e., HUP and YMK) learned Japanese much later in life and were therefore less fluent in Japanese than in English (see Table 1). Rather, this might be related to the relative linguistic closeness between Korean and Japanese as compared to English. However, more careful examination is necessary before we could be certain of the influence of cross-linguistic relatedness of inducing stimuli on synesthetic color.

It should be pointed out that our study utilized a variety of stimuli that enabled us to compare the influence of sound and visual shape similarity at the same time. In contrast, most previous studies showing the important role of visual shape in determining synesthetic color used only Latin alphabets, sometimes accompanied by characters of an additional language that shared visual features with Latin (e.g., Cyrillic) (Brang et al., 2011; Rich et al., 2005; Watson et al., 2012; Witthoft and Winawer, 2006). Indeed, the results of our data-driven clustering analysis showed that characters sharing not only sound similarity but also common visual features are clustered together in the color space, while characters of similar sound outnumber characters of similar visual shapes within the clusters (refer to Fig. 6, Supplementary Tables S1 and S2). On a careful examination of the stimuli clustered together on the CIE *xy*Y color space, characters with phonetic similarity but not visual shape similarity (e.g., "N/n/", "ㄴ/n/", "の/no/") were observed more often than characters with visual shape similarity but no phonetic similarity (e.g., "L/l/", "し/si/", "ㄴ/n/"). In addition, color-matching results from the sequential words seemed to show additive effect of sound and meaning in determining synesthetic color (refer to Fig. 5B, Supplementary Tables S3). Caution is needed to dubb this effect "additive" since the direct statistical comparison was not plausible due to large differences in sample sizes for different sub-groups of pairs. For example, pairs of sequential words sharing both meaning and sound were outnumbered by those sharing only meaning but not sound. However, it should be noted that the sequential words with the same meaning and the same sound tended to show larger difference from the baseline (therefore more similar synesthetic colors) than those with different sound despite much smaller sample sizes. This suggests that the seemingly additive effect of sound to meaning does not solely stem from statistical reason.

Although the current results imply the important role of sound in determining synesthetic color, it might be premature to conclude that sound is the most important factor among other factors including visual shape. It should be noted before jumping to a conclusion that (1) katakana, hiragana, and hangul syllabaries of matched sounds comprised a big portion in the whole stimuli tested, (2) some hiragana–katakana pairs in matched sound bear visual similarity as well (e.g., "か /ka/" and "カ/ka/"), (3) hangul syllabaries with matched initial phonemes also share visual features (the initial consonant, since the hangul syllabaries were composed of a consonant and a vowel; e.g., "나 /na/", "니 /ni/", "네 /ne/"). Therefore, the impact of sound and the impact of shape are intermingled in some cases of our work and also in other previous works.

Indeed, the non-arbitrary association between shape and sound, in turn, the grapheme and phoneme, has been constantly documented in the literature. It has been well known that people tend to associate round, curvy shapes with the sound of "b" while they tend to associate sharp and jagged ones with the sound of "k" (Köhler, 1929; Ramachandran and Hubbard, 2001). Therefore, distilling shape factor off the sound might not be possible. However, such association between sharp shape and sound as in character "k" does not seem to be applied to Japanese and Korean graphemes. In general, hirakana characters tend to have curvature in them, while katakana characters tend to be made up of more straight lines. Most hangul characters are composed of simple line elements, leaving only two graphemes, i.e., "ㅇ (no sound when used in the place of the first phoneme in syllables), /ŋ/ when used as the last phoneme" and "ㅎ (/h/)" as examples of round and curvy shapes. Thus, the relationship between graphemes with sharp visual feature and inducing sharp sound is not obvious in Japanese and Korean graphemes. In future works, it will bear a significance to examine whether a specific visual feature (straight or curvy) or a specific sound character (sharp or soft) influences induced synesthetic color.

One might question the generalizability of the current findings since all four of our participants were multilingual associator-type synesthetes (Dixon et al., 2004). It has been suggested that for associators (or "higher" synesthetes in Ward et al., 2007), who show distinct structural characteristics in a memory-related region of the brain, grapheme-color association is more conceptual (Rouw and Scholte, 2010). In contrast, for projector-type synesthetes *who* "see" colors in the external world (Dixon et al., 2004, or "lower" synesthetes in Ward et al., 2007), who show distinct structural and functional characteristics in the ventral visual processing system, grapheme-color association is more perceptual (Rouw and Scholte, 2007, 2010; Weiss and Fink, 2009). Our exclusive use of associators was certainly a limitation, especially considering the finding of Brang et al. (2011), who proposed visual shape as the determinant for synesthetic color, that the correlation between similarly shaped characters and similar synesthetic color was more prominent in projectors than in associators. We hope to test the current procedure with projector-type multilingual synesthetes in a future study. In the meantime, it is worth mentioning that the relationship between the projector/associator distinction and the determinants of synesthetic color have not been clarified in other studies. Asano and Yokosawa (2011), for example, tested 3 projectors and 3 associators and found that characters of similar sound tended to induce similar synesthetic colors in all 6 synesthetes. Moreover, synesthetic color association was transferred to newly learned characters of similar visual shapes, both in projectors and associators (Mroczko-Wąsowicz et al., 2009).

Finally, the current finding has potential implications for the ongoing debate over the neural underpinnings of grapheme-color synesthesia. It is accepted in the literature that results showing visual shape as the determinant of synesthetic color suggest "hard-wired" cross-associations between low-level areas, possibly between the visual word form area (VWFA) or the posterior temporal grapheme processing area (PTGA) and the color-responsive area (Brang et al., 2010, 2011). In contrast, results showing meaning as the determinant of synesthetic color are often considered to suggest an involvement of high-level concept-related mechanisms. Results showing sound as the determinant of synesthetic color suggest that it is associated with brain regions somewhere in between. In this vein, Asano and Yokosawa (2011) included a discussion of potential skepticism about their findings, positing that the reason why matched characters of the two scripts of Japanese induced similar synesthetic color was not because their sound is similar but because they are not differentiated by the VWFA. Our work could serve to rule out that possibility by showing that characters of similar sound across multiple different languages tended to induce similar synesthetic colors though those inducing stimuli should be discriminated by the VWFA. Our results, however, are not incompatible with those suggesting cross-wiring between low-level areas because our stimuli included syllabaries composed of pairs of a consonant and a vowel, and multi-syllabic words as well as graphemes. Further investigation of the neural underpinnings of grapheme-color synesthesia is warranted to provide a clearer understanding of the role of visual shape, sound, and meaning in determining synesthetic color.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2014.09.032.

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