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Database of Synesthetic Color Associations for Japanese Kanji

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Abstract

Synesthesia is a neurological phenomenon where certain types of stimuli elicit involuntary perceptions in an unrelated pathway. A common type of synesthesia is grapheme-color synesthesia, where visual perception of letters and numbers stimulates perception of a specific color. Previous studies have often collected relatively small numbers of grapheme-color associations per synesthete, but accumulation of a large quantity of data has greater promise for uncovering the mechanisms underlying synesthetic association. In this study, we therefore collected large samples of data from total eight synesthetes. Among them, we obtained over 1000 synesthetic colors associated with Japanese kanji characters for each of two synesthetes, over 100 synesthetic colors for each of three synesthetes, and about 80 synesthetic colors associated with Japanese hiragana, Latin letters, and Arabic numerals for each of three synesthetes. We then compiled the data into a database, called the KANJI-Synesthetic Colors Database (K-SCD), which has a total of 5125 colors for 483, 46, and 46 Japanese kanji, hiragana, and katakana characters, respectively, as well as 26 Latin letters, and 10 Arabic numerals. In addition to introducing the K-SCD, this paper demonstrates the database's merits using two examples, in which two new rules for synesthetic association, “shape similarity” and “synesthetic color clustering,” were found. The K-SCD is publically accessible (http://www.cv.jinkan.kyoto-u.ac.jp/site/uploads/K-SCD.xlsm) and will be a valuable resource for those who wish to conduct statistical analyses using a rich dataset in order to uncover the rules governing synesthetic association and to understand its mechanism.

INTRODUCTION

Synesthesia is a neurological phenomenon in which ordinary stimuli elicit vivid individual perceptions in unrelated pathways, without a corresponding physical stimulus. For example, grapheme-color synesthetes experience subjective colors upon viewing black alphanumeric characters (Dixon, Smilek, & Merikle, 2004; Ramachandran, & Hubbard, 2001). Hearing-color synesthetes similarly “see” colors upon hearing particular sounds (Baron-Cohen, Wyke, & Binnie, 1987). Lexical-gustatory synesthetes “taste” particular flavors and experience particular oral textures upon hearing/reading particular words (Ward & Simner, 2003). These synesthetic perceptions arise without a corresponding sensory input. Therefore, studies on these forms of synesthesia must isolate the process of consciousness from sensory processing, and in doing so may provide a clue to understanding perceptual consciousness. Indeed, brain imaging studies conducted among synesthetic subjects have provided evidence identifying brain regions important for color perception (Hubbard, Arman, Ramachandran, & Boynton, 2005; Nunn et al., 2002; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006). Synesthesia may also provide insight for understanding various aspects of cognition, including mental imaging (Barnett & Newell, 2008), memory (Luria, 1968, Tammet, 2006), art and creativity (Rich, Bradshaw, & Mattingley, 2005, Ramachandran & Hubbard, 2001), and numeracy (Rich et al., 2005).

Most of the knowledge of synesthesia comes from studies on grapheme-color synesthesia, the most common form of synesthesia. In this form, visual perception of letters and numbers (graphemes) induces simultaneous perception of a given color (e.g., the letter “F” may be green and the number “2” may be red) (Cytowic & Eagleman, 2009). There are two important characteristics of this synesthetic experience that should be noted. The first is that the grapheme-color association is surprisingly strong. Rich et al. (2005) showed that grapheme-color pairs were consistent in individuals, with almost no change since childhood. Asano & Yokozawa (2012) showed that kanji-color pairs also have consistency over time. Although a synesthete occasionally acquires different synesthetic color associations from his or her original ones, these new color associations are temporary and lost over time (Mills et al., 2002). Consistency of associations has been used as a diagnostic criterion for synesthesia. Using this criterion, the prevalence of grapheme-color synesthesia has been estimated at anywhere from 1 in 2000 (Baron-Cohen et al., 1996) to 1 in 200 or more (Ramachandran & Hubbard, 2001). The second important characteristic is that the phenomenological aspect of color sensation in grapheme-color synesthesia is very heterogeneous between individuals. Dixon et al. (2004) showed that some grapheme-color synesthetes, termed “projectors,” perceived their associated colors visually in external space, characterizing them as existing “out there on the page.” Others, termed “associators,” perceived their colors in internal space, characterizing them as existing “in my mind’s eye” or “in my head.” Researchers often use this categorization to classify subjects. But, there are currently controversies regarding the validity of the ‘associator’ vs ‘projector’ categorisation (see Chiou & Rich, 2014).

What determines the associations between a grapheme and a color? There is some evidence of commonality between individuals. English-speaking synesthetes often associate synesthetic colors with the initial letter of common color name words, such as “R” being red and “G” being green (Rich et al., 2005; Simner et al., 2005), and with phonological information, such as “I” [aɪ] being white [waɪt] (Rich et al., 2005). However, several studies showed that associations were idiosyncratic between individuals (Laeng, Svartdal, & Oelmann, 2004; Ward, Li, Salih, & Sagiv, 2007). For example, when shown the letter “B”, one individual may report blue, another green, and others yellow. Even synesthetic monozygotic twins report different colors stimulated by the same letter (Rich et al., 2005). These aspects of synesthetic associations suggest that direct correspondences between a grapheme and a color, (a first-order relation), are too elusive to guide the investigation of possible associative mechanisms.

Given this difficulty in establishing first-order relations, recent studies have begun to explore correspondence between the relationships among graphemes on the one hand and the relationships among colors on the other (a second-order relation) (Watson et al., 2012). Brang, Rouw, Ramachandran, and Coulson (2011) showed that similarity between synesthetic colors depended on similarity in the shape of letters. Eagleman (2010) argued that letters early in their respective alphabets (e.g. A, B, C, D) tended to be associated with colors that are more distinct from each other, whereas letters that come later (e.g. V, W, X, Y) tended to be associated with colors that were quite similar to each other. This ordinal relationship has also been found for Japanese hiragana characters (Asano and Yokozawa, 2013).

Accumulating a drastically larger dataset on first- and second-order relationships between graphemes and colors is a promising way, if not the only effective way, to understand the mechanisms underlying synesthetic associations. Such a dataset would allow us to more thoroughly analyze synesthetic mechanisms from various angles. There have been forays into this approach; for instance, Rich et al. (2005) examined 192 adult synesthetes and showed that certain letters and numerals are likely to induce specific colors (i.e., R → red, Y → yellow, D → brown). This study also revealed that synesthetic colors could be derived from parts of conventional sequences such as days of the week, letters, or numerals. Eagleman (2010) launched the web-based Synesthesia Battery, and this project has verified almost 10,000 synesthetes across 15 types of synesthesia and 8 languages. In fact, the ordinal relationship described above was found by using this Battery. Although these databases have great utility, there is one fundamental limitation: The number of synesthetic colors per synesthete is relatively small. Previous studies have often been limited to color associations with only 26 Latin letters (A–Z) and 10 Arabic numerals (0–9), and this relatively small sample per synesthete confines the analysis to the global structure of synesthesia common across synesthetes. If samples per synesthete could be greatly enlarged, we may uncover novel rules governing the fine structure of synesthetic associations.

Therefore, this study took a new approach, complementary to existing databases, where thousands of synesthetic colors were collected from each of two synesthetes, hundreds of synesthetic colors were collected from each of three synesthetes, and about 80 of synesthetic colors from each of three synesthetes. This study had two major goals. The first goal was to create a database that includes synesthetic colors for 483 kanji, 46 hiragana and 46 katakana. Hiragana and katakana are phonetic characters. Kanji are Japanese logographic characters where each character has its own meaning. These characters originated from Chinese and are mainly used to write content words. Kanji have at least two important characteristics as they relate to synesthetic color associations. The first is that kanji are visually comprised of multiple orthographic components, called radicals. Most kanji have two or more radicals, and many kanji characters share common radicals. For example, the characters 決, 河, 活, and 流 share the common *sanzui* radical, "氵," which signifies water. Radicals may be linked to colors, and radical commonality may underlie the generation of synesthetic colors (Asano & Yokozawa, 2012). The second important characteristic is that most kanji have multiple readings, termed the *on-yomi* and *kun-yomi*. *On-yomi* are derived from the original Chinese pronunciation of the character, while *kun-yomi* come from the Japanese pronunciation (Tamaoka, 1991). For example, the kanji 青 (meaning "blue") is pronounced as /sho/ or /sei/ using the *on-yomi*, and /ao/ using the *kun-yomi*. By taking advantage of these specific characteristics of kanji, we succeeded in collecting a number of synesthetic colors from each of five synesthetes associated with kanji characters.

The second goal of this study was to propose new research directions using the developed database. The new database should allow more thorough analyses on the structure of the association between a grapheme and a color. We will illustrate two promising directions here. The first direction is the analysis of first- and the second-order relationships between a given kanji character and synesthetic color, taking advantage of kanji's multifaceted properties for the study of regularities. Asano & Yokozawa (2011, 2012) previously reported that synesthetic kanji-color associations depended on both the semantic and phonological information of the character. The larger samples of kanji-color synesthetic pairs in our database will extend these findings regarding the structure of synesthetic association. The second direction concerns a fundamental yet overlooked issue in the literature: Can any color be a synesthetic color for a synesthete? More explicitly, are synesthetic colors distributed randomly in the color space? Notably, this question cannot be answered without collecting a large amount of data for a single synesthete, which our study provides. We will illustrate techniques of spatial statistics to explore the pattern of distribution of synesthetic colors in the color space.

METHODS

We collected a large number of synesthetic colors for Japanese kanji, hiragana, katakana, Latin letters, and Arabic numerals from each of eight synesthetes. Five of them had synesthetic colors associated with all kinds of characters (kanji-color synesthetes), and others had synesthetic colors associated with hiragana, Latin letters, and Arabic numerals (hiragana-color synesthetes). The five kanji-color synesthetes participated in two experiments. The first employed a color-selection task to determine the synesthetic colors that they experienced when stimulated with printed graphemes comprising kanji, hiragana, katakana, Latin letters, and Arabic numerals. The second experiment employed a color-matching task to determine their synesthetic color associations for Latin letters and Arabic numerals displayed on a CRT monitor. The three hiragana-color synesthetes participated only in the color-matching task.

Participants

Eight Japanese synesthete (five females: SH, AH, MH, AM and YH; three males: SO, HS and YK; age range = 18–21 years) received payment (dependent on experiment time) for their participation in the experiments. SH and SO were self-reported projector-type synesthetes and the others were self-reported associator-type synesthetes. Their scores on the color match consistency test were below 1.0, indicating a consistent and authentic synesthetic experience (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007).

Color selection experiment

Visual stimuli

The test stimuli comprised individual black graphemes printed centrally on a white card, called the “character card” (127 mm × 89 mm). Character cards used in elementary education included 482 kanji, 46 hiragana (あ–ん), 46 katakana (ア–ン), 26 Latin letters (A–Z), and 10 Arabic numerals (0–9). Each kanji, hiragana, and katakana character was printed in 42-point HG textbook font (about 15 mm × 15 mm), and each Latin letter and Arabic numeral was printed in 72-point Arial font (about 25 mm × 33 mm). Character cards were placed on a desk covered by a black cloth and illuminated by a D65 daylight fluorescent lamp, which has a high color-rendering index of 98 (FL20S D-EDL-D65; TOSHIBA Inc., Tokyo, Japan). The viewing distance was approximately 40 cm.

Procedure

The participant was asked to view a character card and select the color(s) that best matched their perceived synesthetic color using color chips from the *Munsell Book of Color, Matte Finish Collection*. More specifically, in each trial, they picked up a character card, placed it on the center of the desk, observed the character, and selected one of the five basic colors (5R, 5G, 5B, 5Y, 5P) that most resembled their synesthetic color. Next, they examined all four sheets for the selected basic color from the *Munsell Book*, and selected the color chip that best matched the synesthetic color. Finally, they wrote the color chip's Munsell code in a blank space on the character card. If they perceived multiple synesthetic colors for a character, the procedure was repeated. The part of the character where they perceived each synesthetic color was marked by a box. Trials were blocked for kanji, hiragana, and katakana (40 blocks of 12 or 13 cards for kanji; 4 blocks of 12 or 10 cards for hiragana or katakana, respectively) and the order of the trials was quasi-randomized.

Two of the participants, SH and AH, performed a longer-term experiment (480 kanji characters) than the others did (240 kanji characters). As the experiment was expected to be very time-consuming, we decided to allow SH and AH to perform the experiment in their home in their free time, after practice sessions were performed in the laboratory. Care was taken to ensure that the experiment was performed in a constant visual environment. The other six synesthetes performed the experiment in our laboratory. All participants was instructed to view the cards under the high color-rendering lamp, to do the experiment regularly, and to keep an experimental diary. The diary confirmed that it took a long time to complete the experiment. In synesthetes that had kanji-color associations, SH spent 16 hours 45 minutes, 1 hour 4 minutes, and 54 minutes for the kanji, hiragana, and katakana sets, respectively, over a total of 17 days. AH spent 53 hours 30 minutes, 2 hour 4 minutes for the kanji and hiragana sets, respectively, over a total of 23 days. Because of this very time-consuming of experiment, the experimenter did not employ the color-selection task of katakana for AH. SO spent 14 hours 41 minutes, 54 minutes, and 40 minutes for the kanji, hiragana, and katakana sets, respectively, over a total of 7 days. MH spent 10 hours 11 minutes, 49 minutes, and 57 minutes for the kanji, hiragana, and katakana sets, respectively, over a total of 7 days. HS spent 9 hours 25 minutes, 1 hour 4 minutes, and 55 minutes for the kanji, hiragana, and katakana sets, respectively, over a total of 5 days. The experimenters checked for mistakes in recording of the Munsell codes, found a total of 13 typos of the Munsell codes (2 typos for SH, 6 typos for AH; 1 typos for SO; 2 typos for MH; 2 typos for HS), and excluded them

Color matching using a CRT monitor

Visual stimuli

For the 26 Latin letters and 10 Arabic numerals, the color coordinates (CIE

L*a*b*) of each synesthetic colors were determined by a color-matching task using a CRT monitor (1280 × 1024 pixels, 100 Hz, NANAO, FlexScan F980). The test character in Arial font (3° visual angle) was located on the left side (3° from center) of the screen and a reference color patch was located on the right side (3° from center). The test character was black and the background color was gray (CIE x = .284, y = .341, Y = 30.0). The monitor was calibrated with a chromameter (CS-100A; Konica Minolta, Tokyo, Japan), using Mcalibrator2 software (Ban & Yamamoto, 2013).

Procedure

In the laboratory setting, the participant was asked to adjust the color of the displayed reference patch so that it best matched their perceived synesthetic color of the test character. More specifically, after 3 min of dark adaptation followed by 2 min of light adaptation, they started the color-matching trials. First, the character and the reference patch were displayed on the CRT monitor. The initial color of the reference patch was set to the chromaticity of the Munsell chip as determined in the color selection experiment, but with random variation of the CIE L*a*b* color coordinates of ±5, 5, or 10. Next, the participant adjusted the color patch with a digital input device until they felt that it matched her perceived synesthetic color. The input device allowed her to alter the L*a*b* color coordinates of the color patch independently by ±0.3, 1, and 1. The trial order was randomized.

Analysis

We used the CIE L*a*b* color space to analyze the distribution of synesthetic colors. The CIE L*a*b* coordinates specify colors using values along three axes: light and dark (L*), red and green (a*), and blue and yellow (b*). An L*a*b* color space is a uniform color space, where a given spatial distance corresponds to an equivalent perceptual difference; that is, one unit corresponds approximately to one just-noticeable difference. This uniformity would be suitable to interpreting the distribution of synesthetic colors when analyzing based on a distance metric, as described below.

The distribution of synesthetic colors was investigated using spatial statistics analysis, performed with spatstat (Baddeley, 2010) software, which is an R package for analyzing a spatial point pattern. Such point patterns fall into three general categories: random, clustered, and uniform (Fig. 1: top) (Bailey & Gatrell, 1995). In a random pattern, any point is equally likely to occur at any location, and points are not affected by other points. In a clustered pattern, many points are concentrated in some regions and are sparse in others. Lastly, in a uniform pattern, every point is as far as possible from all nearby points. We considered the distribution of synesthetic colors in an a*b* chromaticity plane to be a 2D point pattern, and then explored which distribution patterns the synesthetic colors exhibited.

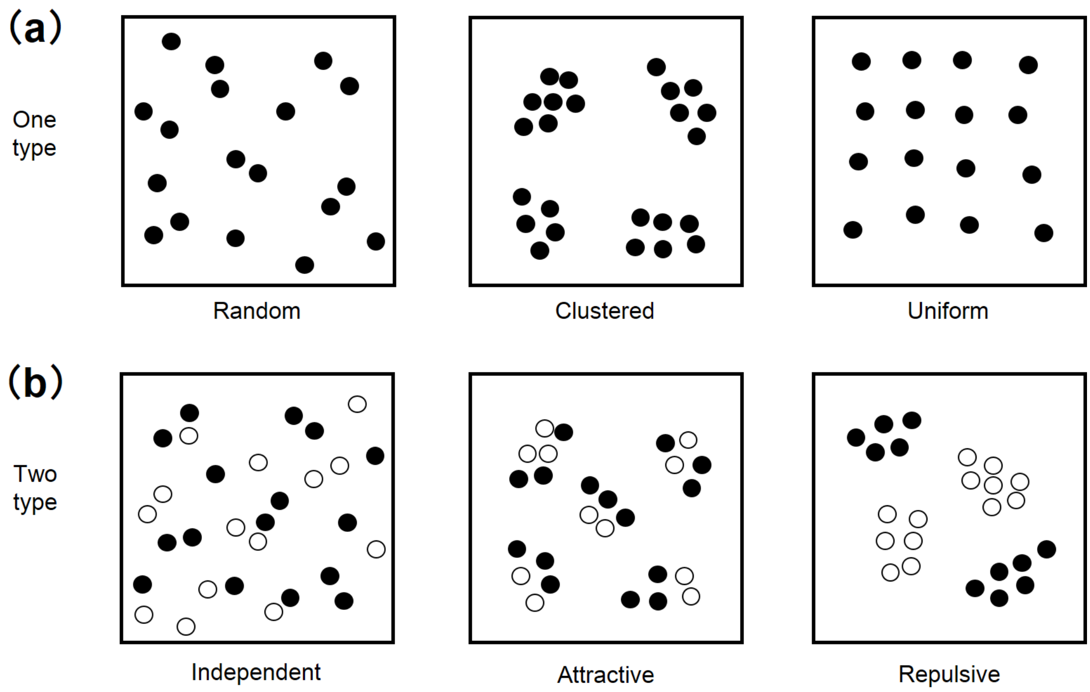


Figure 1. Examples of types of point pattern classified with spatial statistics. (a) When objects (points) comprising a single type, possible point patterns are random, clustered, or uniform. (b) When objects comprise two types, possible point patterns are independent, attractive, or repulsive.

More specifically, our exploratory analysis had three steps. First, the synesthetic color's point pattern was visualized in the a*b* chromaticity plane. Second, the density of the point pattern was estimated by Kernel estimation using the *density()* function. Kernel estimation calculates the density of points within a specified search radius (σ = 8.46) around each point. Third, the type of the synesthetic color's point pattern was judged by the L-function, computed from Ripley's K-function, which is defined as

$$K(r) = E(r)/\lambda. \quad (1)$$

In the K-function, which is a function of search radius r, $E(r)$ is the expected number of points within radius r of an arbitrary point. λ is the density of points (synesthetic colors per unit region), estimated by $\lambda = n / a$, with n points (synesthetic colors) in a given region a. If a point pattern is random, the K-function becomes

$$K(r) = \pi r^2. \quad (2)$$

The L-function can be computed from the K-function as

$$L(r) = \sqrt{K(r) / \pi} - r. \quad (3)$$

Using this L-function, we could classify the synesthetic color's point pattern as being one of the three types: random when L (r) = 0, clustered when L (r) > 0, or uniform when L (r) < 0, as shown in Fig. 2a.

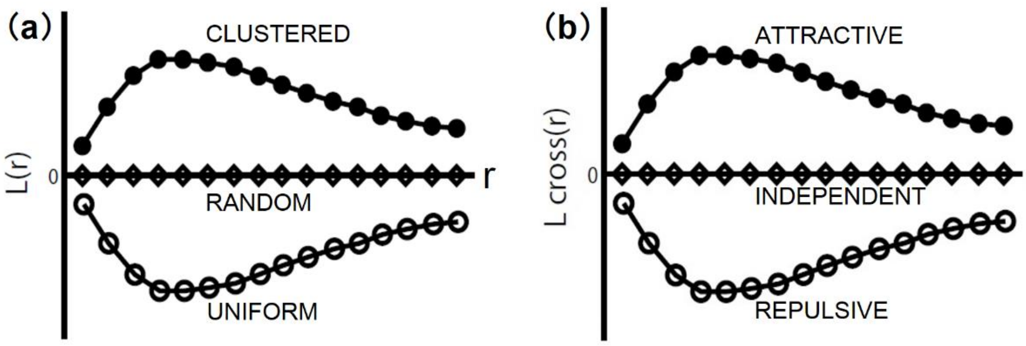


Figure 2. Example plots of expected L-function and cross L-function for the each of the three kinds of point patterns in Fig. 1a and Fig. 1b. For the definition of the L-function, see the main text. (a) Examples when objects comprise one type. If L-function is a constant 0, it indicates a random pattern, if it is positive, a clustered pattern, and if it is negative, a uniform pattern. (a) Examples when objects comprise two types. If L-function is a constant 0, it indicates an independent pattern, if it is a positive value, an attractive pattern, and if it is a negative value, a repulsive pattern.

For further analysis, we referred to an extension of the L-function, called the cross-L function, which can evaluate the dependency of two point patterns. This function is helpful in investigating the interrelation between synesthetic color stimulated by different groups of graphemes, such as by grapheme types (e.g. kanji vs. hiragana) or by learning grade, and therefore complexity, of kanji (e.g. the simple 一 and 二 vs. the more complex 雨 and 雲). The dependency of point patterns pairs was divided into three categories (Bailey & Gatrell, 1995), independent, attractive, or repulsive, as shown in Fig. 1. Independent is when no dependency was observed between the two patterns, attractive is when the two patterns collect at specific places, and repulsive is when the two patterns exclude each other. These types of synesthetic colors point patterns were judged by the cross L-function, which is computed from Ripley's cross K-function, defined as

$$K_{AB}(r) = E(r) / \lambda_B. \quad (4)$$

Here, $E(r)$ is the expected number of members of point pattern *B* within a given radius *r* of any arbitrary member of the point pattern *A*. λ_B is the density of the point pattern *B*, which can be estimated as n_B/a, with a total of n_B members of the point pattern *B* and a given region *a*. The cross L-function can be computed from the cross K-function as

$$L_{AB}(r) = \sqrt{K_{AB}(r) / \pi} - r. \quad (5)$$

Using this cross L-function, we could classify the synesthetic color point pattern as being one of the three types: independent when $L_{AB}(r) = 0$, attractive when $L_{AB}(r) > 0$, or repulsive when $L_{AB}(r) < 0$, as shown Fig. 2b.

RESULTS

Synesthetic colors associated with kanji characters

We investigated the synesthetic colors associated with 482 kanji characters for SH and AH, and 240 kanji characters for SO, MH, HS. We obtained a total of 4187 colors from five synesthetes, as specified using the Munsell color system. Additionally, about 80 synesthetic colors from each of three synesthetes associated with hiragana characters. Notably, the number of synesthetic colors was larger than the number of kanji characters investigated. On average, a kanji character was associated with 2.26 colors for SH, 4.61 colors for AH, 1.92 colors for SO, 1.55 colors for MH and 0.80 colors for HS. In the below, the thousands of synesthetic colors for kanji characters were analyzed.

The first question we asked is "How is a kanji character associated with multiple colors?" There seem to be at least four ways for SH. The first was that synesthetic colors depended on the component radicals rather than the character as a whole, and that kanji characters are often comprised of multiple radicals. For example, the character "決" was perceived in two parts, the aforementioned *sanzui* radical "氵" perceived as yellow, and the remaining "夬" component, perceived as red (Fig. 3a). This radical dependency was also seen at synesthete SO, MH and HS. The second way was when synesthetic colors depended on pronunciation, and a kanji characters often have multiple readings. For example, the character "千" was perceived as yellow when read by its *on-yomi* (/sen/), while it was perceived as red when read by its *kun-yomi* (/chi/) (Fig. 3b). The third way was that a kanji character sometimes had an overall color that differed from the local colors that were usually associated with its radicals. For example, the character "聞" is comprised of two radicals ("門" and "耳"), which were perceived to have their own local colors (yellow-red and red-purple, respectively), but the character as a whole was perceived to be green (Fig. 3c). The fourth way was that a kanji was sometimes simply perceived to be two different colors. For example, the upper radical ("ハ") of the "谷" character was sometimes perceived as purple-blue and sometimes as yellow (Fig. 3d). For synesthete AH, almost of synesthetic colors depended on finer component parts of kanji characters beyond radicals. For example, the character "決" was divided into radical "氵" and the "夬" as well as SH, but then the"夬" was divided into the "ユ" and the remaining "人". The *sanzui* "氵" perceived as red, the "ユ" component, perceived as different red, and the "人" component, perceived as yellow (Fig. 4a). The character "識" was associated with most synesthetic colors (12 colors), and these synesthetic colors depended on so detailed components of the kanji character (Fig. 4b).

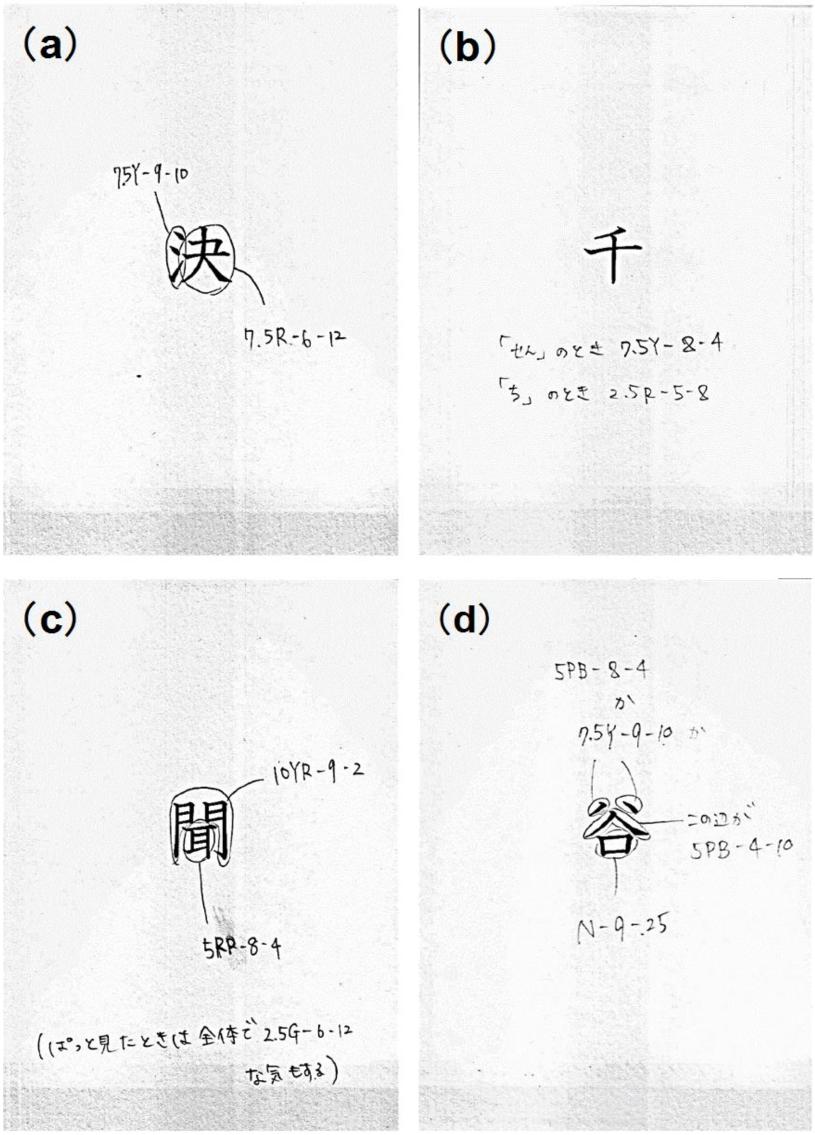


Figure 3. Representative results of the color-selection experiment from a projector-type synesthete SH. Each figure is a scanned character card. The synesthete wrote the Munsell codes and supplemental comments in the blank spaces on the character cards. (a) An instance where synesthetic colors varied by radical. The “決” was divided into the “氵” radical and the remaining “夬” component, each of which had a distinct color. (b) An instance where synesthetic colors varied by sound. She described that when “千” was read by its *on-yomi*, “sen”, the color was 7.5Y-8-4, and when it was read by its *kun-yomi* “chi”, the color was 2.5R-5-8. (c) An instance where the global color differed from local colors. She added to her notation of the individual colors that “At a glance, I feel also that the whole character is 2.5G-6-12”. (d) An instance of the case where the synesthetic color switched for the same part. She described that the upper part (“ハ”) of “谷” was sometimes 5PB-8-4, but sometimes 7.5Y-9-10.

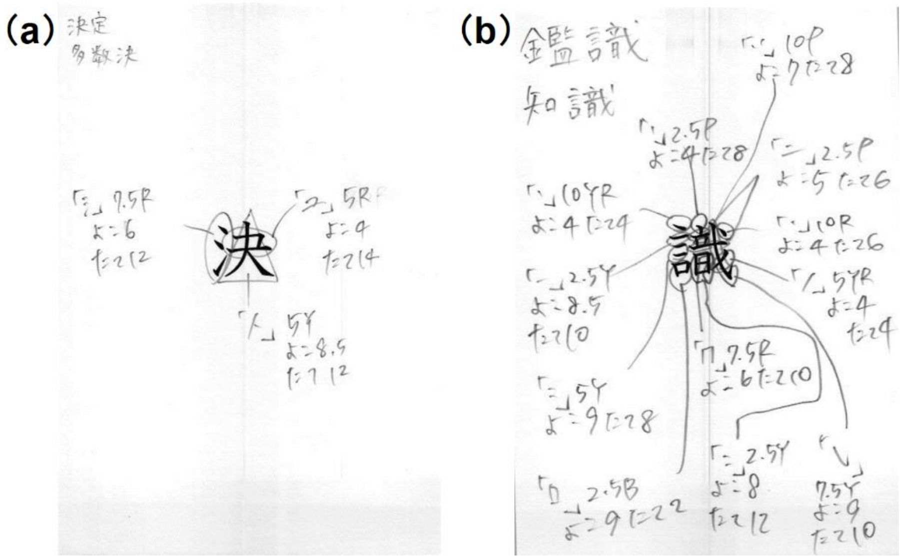


Figure 4. Representative results of the color-selection experiment from an associator-type synesthete AH, in similar fashion to Fig. 3. Both (a) and (b) shows instances where synesthetic colors varied by finer components beyond radicals. (a) The “決” was divided into the “氵” radical and the “夬” component, and even the “夬” was divided into the “ユ” into the remaining “人”, each of which had a distinct color. (b) the “識” was associated with most the synesthetic colors (12 colors), which depended on highly-detailed components of the kanji character.

We also investigated 46 hiragana characters, 46 katakana characters, 26 Latin letters, and 10 Arabic numerals for SH, SO, MH and HS and these characters other than katakana for AH. Some of these characters were associated with two colors for SH and AH and thus there was a slightly greater number of synesthetic colors than characters (SH: 144 colors for 128 graphemes; AH: 192 colors for 82 graphemes; SO: 144 colors for 128 graphemes; MH: 144 colors for 128 graphemes; HS: 144 colors for 128 graphemes). When these were added with the kanji, there was a total of 1229 (SH), 2349 (AH), 429 (SO), 325 (MH) and 191 (HS) synesthetic colors collected, respectively.

Figure 5 shows all of these colors in the L*a*b* color space for each of five kanji-color synesthetes. The synesthetic colors seemed to be widely distributed in the three axes. To take a closer look, we projected these distributions in three 2D planes, a* vs. b* (Fig. 5b, f, j, n, r), L* vs. a* (Fig. 5c, g, k, o, s), and L* vs. b* (Fig. 5d, h, l, p, t). Figure 6 shows all of synesthetic colors for each of the three hiragana-color synesthetes, in similar fashion to Fig. 5. For both types of the synesthetes, the point pattern in chromatic plane seemed to show some regions where the points were concentrated and where there were few points (a* vs. b*), suggesting that synesthetic colors were neither randomly nor uniformly distributed in the color space. This types of bias was also present for luminance dimension. Focusing on the point pattern along the luminance axis for kanji-color synesthetes (L* vs. a* and L* vs. b), there were a small number of dark colors with L* less than about 30 (Fig. 5c, d, g, h, k, l, o, p, s, t). For hiragana-color synesthetes AM, it can be seen that there were few dark colors with L* less than about 30 (Fig. 6c, d). In contrast, For YK and YH, it can be seen that there were dark colors with L* less than about 30 (Fig. 6g, h, k, l). Taken together, it appears that the synesthetic colors are distributed more heavily in some regions in the color space. Detailed analyses of this tendency are investigated at greater length using spatial statistics in the “Example of applications” section below.

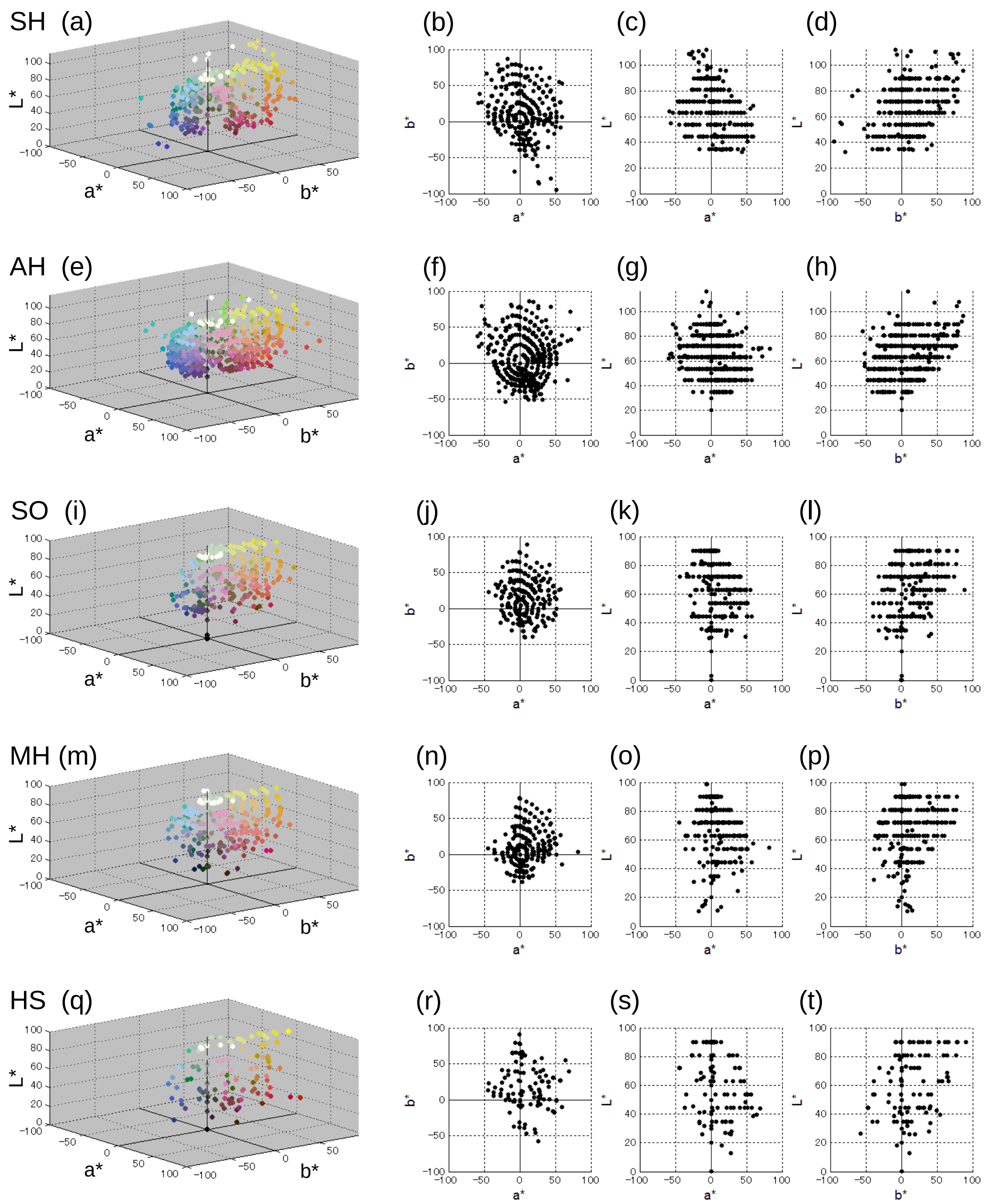


Figure 5. The distribution of synesthetic colors collected from kanji-color synesthetes in CIE L*a*b* uniform color space. Synesthetic colors of kanji, hiragana, and katakana were transformed from the Munsell values to CIE L*a*b* values. (a) synesthetic colors of SH in L*a*b* color space, (b) those projected onto the a* vs. b* chromaticity plane, (c) those projected onto the L* vs. a* plane, and (d) those projected onto the L* vs. b* plane. (e ~ t) for AH, SO, MH, and HS in similar fashion to (a,b,c,d).

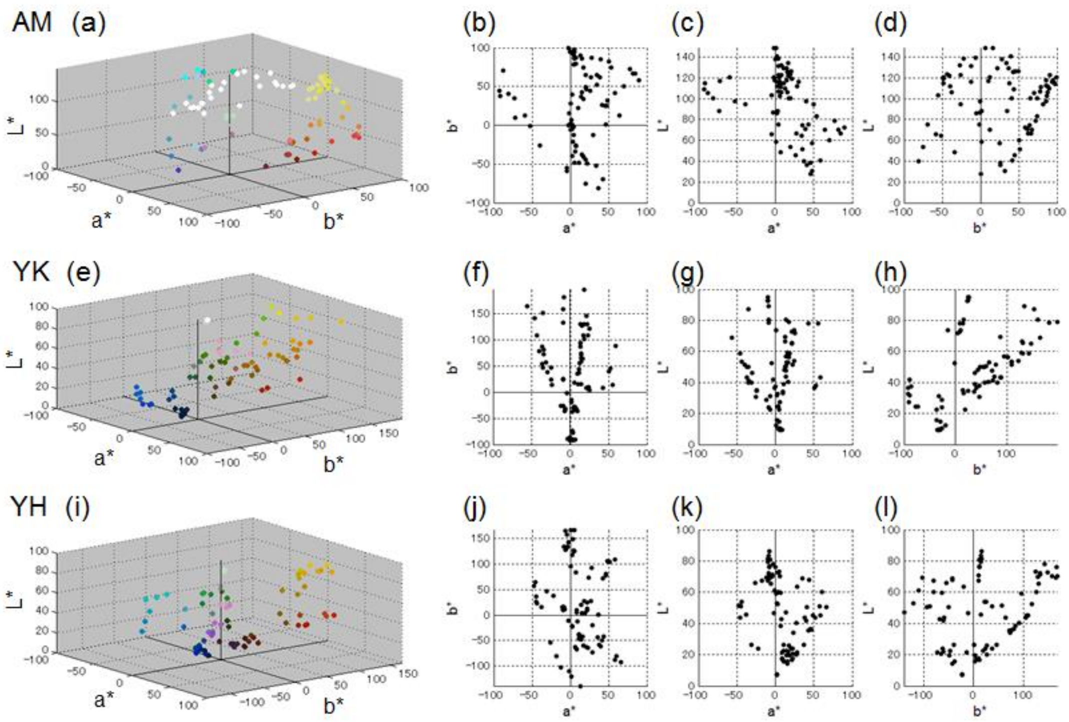


Figure 6. The distribution of synesthetic colors collected from hiragana-color synesthetes in CIE L*a*b* uniform color space, in similar fashion to Fig. 5. (a) synesthetic colors of AM in L*a*b* color space, (b) those projected onto the a* vs. b* chromaticity plane, (c) those projected onto the L* vs. a* plane, and (d) those projected onto the L* vs. b* plane. (e ~ i) for YK and YH in similar fashion to (a,b,c,d).

We compiled these diverse synesthetic colors and the associations between kanji characters and colors into a database that could be helpful for the study of grapheme-color synesthesia. In the following sections, we describe the contents of the database and introduce new research directions that this database has opened up.

Database contents

Figure 7 shows a section of the new database. The database denotes not just the synesthetic colors associated with each kanji character, but also gives additional information for each character, such as radicals and pronunciations that affected synesthetic colors, as described above (Table 1). This auxiliary information is potentially useful in analyzing first- and second-order relations of the synesthetic associations. The database was implemented as a Microsoft Excel book file that comprising multiple sheets, including the kanji, hiragana, katakana, English graphemes (letters and numerals), and search sheets. The details of the contents of each sheet will be presented below.

character	block	trial	session	code	grade	radical	strokes	on-reading	on-reading (hepburn)	kun-reading	kun-reading (hepburn)	constituent	number of colors	color appearance	subjective report	color1	color2	color3
男	1	10	1	7537	1	田	7	ダン・ナン	dan・nan	おとこ	otoko	田力男	2	A		5PB-4-12	5PB-5-12	
青	1	12	1	9752	1	青	8	ショウ、セイ	sho, sei	あお、あお・い	ao, ao・i	月青	2	*D	whole is blue and part of "月" is 7.5Y-8.5-12	5PB-4-12	7.5Y-8.5-12	
年	2	6	2	5E74	1	干	6	ネン	nen	とし、とせ	toshi, tose	ノ丿十干年	1			5Y-9-8		
先	2	7	2	5148	1	儿	6	セン	sen	さき	saki	土儿先	1			5Y-8.5-10		
白	3	11	2	767D	1	白	5	ハク、ビャク	haku, byaku	しろ、しら、し	shiro, shira,	白	1			N-9-0.25		
子	3	12	2	5B50	1	子	3	シ	shi	こ、ね	ko, ne	子	1			7.5GY-8.5-2		
糸	4	2	3	7CF8	1	糸	6	シ	shi	いと	ito	幺小糸	2	A		N-8-0.75	N-7-0.25	
字	4	3	3	5B57	1	子	6	ジ	ji	あざ	aza	宀子字	1			N-2-0.5		
王	5	4	4	738B	1	王	4	オウ	o	きみ、おおき	kimi, okimi	王	1			2.5YR-6-14		
三	5	7	4	4E09	1	一	3	サン	san	み、みっ・つ	mi, mitsu・tsu	一二三	1			2.5PB-8-6		
入	6	6	4	5165	1	入	2	ニュウ、ジュ、ジュウ	nyu, ju, ju	い・れる、はい・る	i・reru, hai・ru	入	1			7.5Y-9-6		
手	6	7	4	624B	1	手	4	シュ	shu	て、た	te, ta	手	1			5PB-5-10		
水	7	1	5	6C34	1	水	4	スイ	sui	みず、みな	mizu, mina	水	1			7.5B-8-4		
正	7	5	5	6B63	1	止	5	セイ、ショウ	sei, sho	ただ・しい、ま	tada・shii, masa・	止正	1			2.5Y-9-2		
犬	8	4	5	72AC	1	犬	4	ケン	ken	いぬ	inu	大丶犬	2	A		5PB-7-8	7.5Y-9-10	
見	8	5	5	898B	1	見	7	ケン	ken	み・る	mi・ru	目儿見	1			10RP-8-6		
休	9	8	6	4F11	1	人	6	キュウ	kyu	やす・む	yasu・mu	亻木休	2	A		2.5GY-8.5-1	7.5GY-6-10	
気	9	9	6	6C17	1	气	6	キ、ケ	ki, ke			气〆気	1			10GY-6-10		
六	10	8	6	516D	1	八	4	ロク、リク	roku, riku	む・つ	mu・tsu	亠八ハ六	1			2.5YR-6-14		
木	10	9	6	6728	1	木	4	ボク、モク	boku, moku	き	ki	木	1			2.5G-5-10		
車	11	1	7	8ECA	1	車	7	シャ	sha	くるま	kuruma	車	2	*D	whole is N-2-0.25, but also appear 5R-4-14 partly	N-2-0.25	5R-4-14	

Figure 7. A screen shot of the kanji sheet in the K-SCD.

Table 1

Synesthetic color information and auxiliary information for characters in the database

Class	Subclass	Explanation of subclass
Color		Munsell color system, CIE xyY and CIE L*a*b*
Elemental	Grade	the year when a given kanji character was taught in Japanese primary schools
	Radical	orthographic conponets of kanji characters
	On-reading	chinese reading of kanji
	Kun-reading	Japanese reading of kanji
	Constituents	separable parts of a kanji caharacer
Supplemental	Strokes	the number of kanji strokes
	Number of colors	the number of colors in a character
	Color appearance	patterns of way of perceiving synesthitic colors
	Subjective report	additional information on the synesthete's introspection about the "Color appearance"
	Overall color	the overall synesthetic color of a kanji character

Note. Color class includes chromaticity coordinates for Japanese kanji, hiragana, and katakana, Latin letters, and Arabic numerals. The elemental class contains subclasses relating to various components of kanji characters. The supplemental class has subclasses relating to complementary information about kanji characters or perceived synesthetic colors.

Kanji sheet

The kanji sheet had kanji characters in rows and various auxiliary information associated with each kanji character in columns, hereafter called "classes." The classes comprised three types: color class, elemental class, and supplemental class. The color class contained a color defined using three types of chromaticity coordinates—the Munsell color system, CIE xyY, and CIE L*a*b* color coordinates—in conjunction with a visualization of the color by coloring the cell background.

The elemental class was the category of the various components in the kanji character. This had subclasses of "radical", "constituent" "*on-yomi*", "*kun-yomi*" and "grade". "Radical" described common sub-elements found in different kanji characters. The "constituent" subclass showed component parts of the kanji character, set to investigate the influence of all component shapes, not limited solely to radicals. The "*on-yomi*" and "*kun-yomi*" subclasses list the various readings of the kanji character, as previously described. "Grade" shows the year when the given kanji character is taught in Japanese elementary school (first through sixth grade), as stated by the Ministry of Education, Culture, Sports, Science and Technology of Japan's appendix "List of Kanji by School Year" of "Course of Study for Elementary School". As the school year in which kanji characters are taught is standardized by the Ministry, this item will be potentially useful for the research on the longitudinal tendency of synesthetic colors.

The supplemental class was a category containing complementary information about kanji characters or synesthetic colors. This was divided into five subclasses, "strokes," "number of colors," "color appearance," "subjective report", and "overall colors." "Strokes" was the number of strokes in the kanji character. "Number of colors" showed the number of synesthetic colors associated with the character. "Color appearance" categorized the various ways that the synesthete perceived the colors, divided into nine categories: (a) colors were divided into each part ("component") of the kanji; (b) colors switched at within the same part; (c) colors were divided into each part, but there were a different overall color when seeing a character as a whole; (d) there was an overall color when seeing a character as a whole, but there was also local color; (e) the color changed depending on the reading or meaning; (f) colors were divided into each part and also colors switched in some part; (g) colors were perceived "somewhere"; (h) there was a part with no color; and (i) there were colors in the mind's eye. Lastly, "subjective report" contained additional information on the synesthete's subjective thoughts about the information contained in color appearance. "Overall colors" was overall synesthetic color of a kanji character.

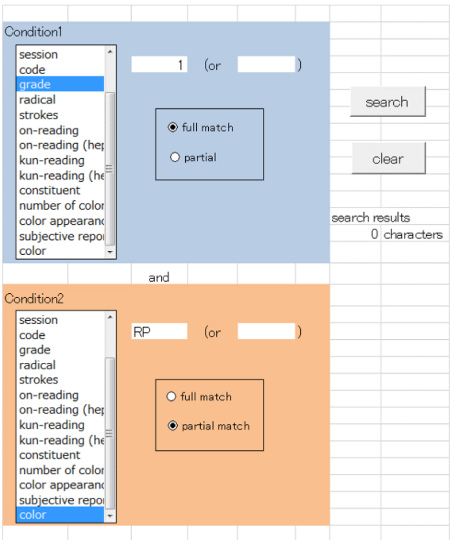
Hiragana, katakana, and English grapheme sheets

These sheets had each character in a row and select classes or subclasses associated with the character in the columns. The hiragana and katakana sheets had the color class and the supplemental class (only "number of colors" and "subjective report"). The English graphemes sheet (letters and numerals) had only color class, determined as described in the Methods section, where two color coordinates of CIE xyY and CIE La*b* were measured in the CRT monitor color-matching task.

Search sheet

The search sheet can take arbitrary data from the kanji sheet. Figure 8 shows a screenshot of the search sheet. The search sheet has two functions for searching the database. The first was an OR search, where a user can assign a maximum of two factors per subclass. The second was an AND search, where a user can assign a maximum of two conditions. For these searches, search terms may be fully or partially matched. If a user would, for example, like to search for data on kanji that are first-grade level and were associated with red-purple synesthetic colors, as described in Fig. 8a, the user inputs "1" for grade with full match selected as condition 1 and inputs "RP" for color with partial match selected as condition 2. Figure 8b shows the result of this example search, containing all returned entries fulfilling the condition.

(a)



(b)

character	block	trial	session	code	grade	radical	strokes	on-reading	on-reading (hepburn)	kun-reading	kun-reading (hepburn)	constituent	number of colors	color appearance	subjective report	color1
見	8	5	5	898B	1	見	7	ケン	ken	み・る	mi・ru	目儿見	1			10RP-8-6
女	18	7	11	5973	1	女	3	ジョ、ニョ	jo, nyo	おんな、め	onna, me	女	1			7.5RP-5-12
二	29	4	18	4E8C	1	二	2	ニ、ジ	ni, ji	ふた・つ	futa・tsu	二	1			5RP-8-6
耳	37	12	22	8033	1	耳	6	ジ、ニ	ji, ni	みみ	mimi	耳	1			10RP-8-6

Figure 8. Screenshots of the search function of the K-SCD, showing a sample of (a) the search field and (b) the search results.

Example of applications

Exploring the relationship between the multidimensional natures of kanji and synesthetic colors

Our database was useful for exploring the regularity in the association between kanji characters and synesthetic colors. Here, we wanted to illustrate this with an example in which the first- and the second-order relationships of the association were examined, focusing on SH that had four ways of grapheme-color associations.

At first, we focused on the first-order relation; namely, which radicals were most frequently associated with what colors? To answer this, we determined the most frequent color among the five basic Munsell colors. In the database search sheet, we assigned each basic color ("R", "Y", "G", "B", and "P") for color with partial match selected as condition 1. The most frequent color was yellow: 332 of 482 kanji characters had a yellowish color. We then explored the relationship between these yellowish colors and various radicals to check for common radicals or constituents in the 332 detected characters. It was found that yellowish colors were associated with the *sanzui* "氵", *tsukanmuri* "ツ", and *ninben* "イ" radicals. We then considered a possible second-order relationship: Do characters with shapes similar to these radicals have similar colors? To answer this, we examined three katakana characters with similar shape, "シ", "ツ", and "イ". Interestingly, these katakana characters also had a yellowish color. Taken together, for the most frequent color (yellowish), characters with similar shape have similar colors.

Analysis of the global structure of synesthetic colors in the chromaticity space

Here we wanted to provide an answer for the question presented in the Introduction section: are synesthetic colors distributed randomly in the color space? As mentioned above, the distribution of synesthetic colors suggested the possibility that the point patterns were not random or uniform but rather were clustered (Fig. 5b, f, j, n, r). To confirm this possibility statistically, we analyzed the point pattern of synesthetic colors using several techniques of spatial statics, which had three steps, as noted in the Methods section. At first, we projected the colors to the a*b* chromaticity plane, visualizing the point pattern of synesthetic colors (Fig. 9a, c, e, g, i). Second, we estimated the density of the point pattern by Kernel estimation (Fig. 9b, d, f, h, j). To clarify the distributions of synesthetic colors for kanji-color synesthetes, the density of chromatic colors was also estimated after excluding the achromatic colors (SH; 211 samples; AH; 145 samples; SO: 78 samples; MH: 61 samples; HS: 75 samples). As clearly shown in Figure 9b, d, f, h, j, it was found that there were clusters of chromatic synesthetic colors for the kanji-color synesthetes. For the hiragana-color synesthetes, as clearly shown in Figure 10b, d, f, there were many clusters of synesthetic color. High-density and low-density region for each of syensthetes are summarized Table 2. For two kanji-color synesthetes, SH and AH, over 1000 synesthetic colors were concentrated in multiple regions in the a*b* chromaticity plane. For three kanji-color synesthetes, SO, MH, and HS, over 100 synesthetic colors were concentrated in original point.

Finally, to confirm these synesthetic color clusters, we analyzed the type of point pattern using the L-function (Fig.11: kanji-color syesthetes; Fig. 12: hiragana-color synesthetes). As shown in Fig. 11, 12, the L-function returned positive values greater than the confidence intervals. This suggests that synesthetic colors are concentrated in multiple regions in the color space, that is, they form "synesthetic color clusters".

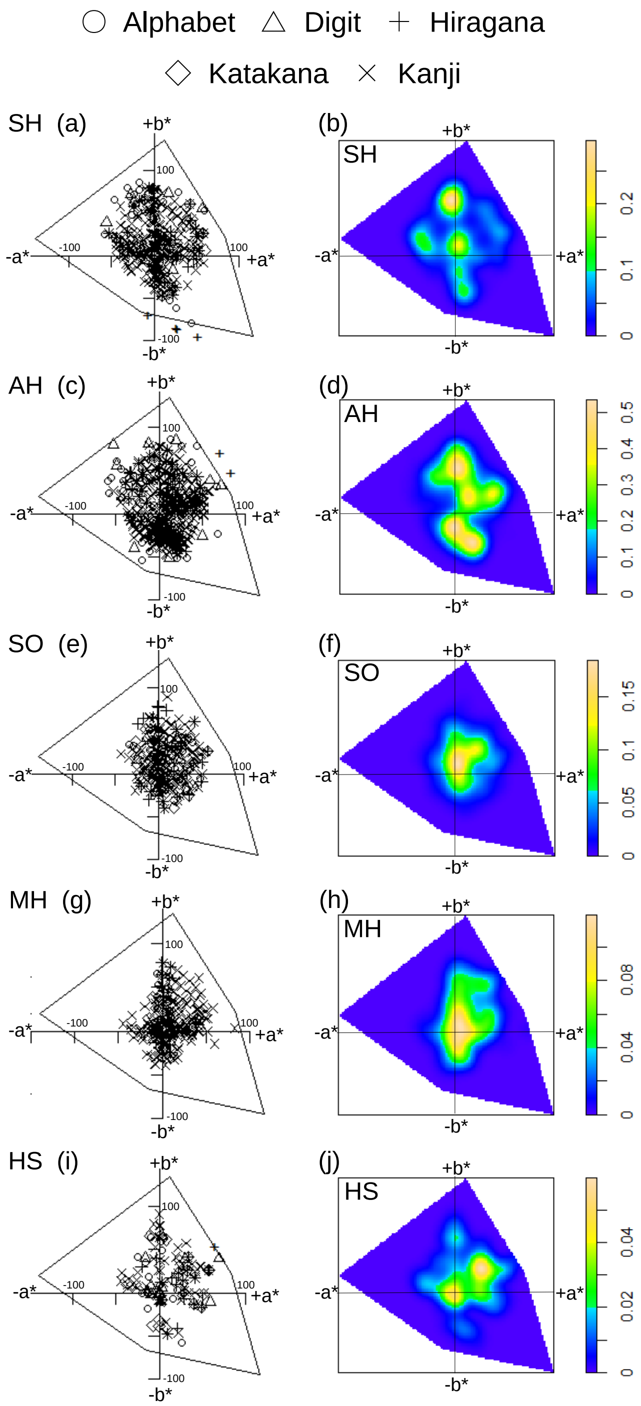


Figure 9. (a, c, e, g, i) The point patterns of synesthetic colors in the a*b* chromaticity

plane for kanji-color synesthete SH, AH, SO, MH and HS respectively. (b, d, f, h, j) The density plot of synesthetic colors as estimated by Kernel estimation for each synesthete. Achromatic synesthetic colors were excluded and then the density was estimated as before. Color bars denote density λ of the points within a specified search distance (σ = 8.46) of each point.

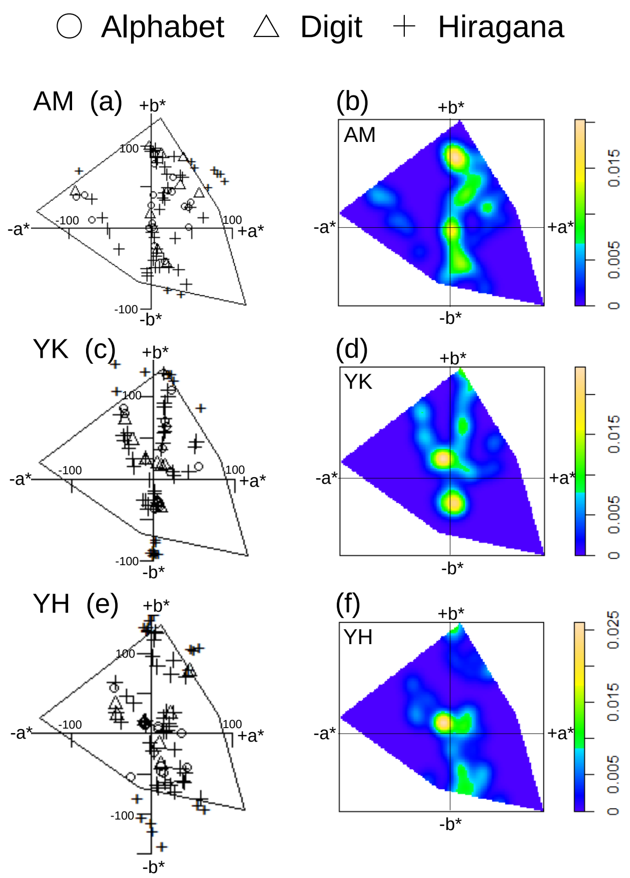


Figure 10. (a, c, e) The point patterns of synesthetic colors in the a*b* chromaticity plane for hiragana-color synesthete AM, YK and YH respectively, in similar fashion to Fig. 9.

Table 2

High-density and low-density region of synesthetic colors in in the a*b* chromaticity plane

synesthete	the number of chromatic colors	high-density		low-density	
		region	[a*, b*]	region	[a*, b*]
kanji-color synesthete					
SH	1018	original point	[0, 15]	red	[55, 25]
		yellow	[5, -75]		
		blue	[10, -45]		
		green	[-40, 15]		
AH	2204	yellow-red	[15, 20]		
		yellow	[0, 65]		
		red	[45, 20]		
		blue	[0, -20]		
		blue-purple	[20, -25]		
SO	351	original point	[0, 10]		
MH	264	original point	[5, 0]		
HS	116	original point	[0, 0]	yellow	[0, 70]
		red	[55, 25]	blue	[5, -50]
hiragana-color synesthete					
AM	80	original point	[0, 0]		
		yellow	[0, 100]		
		blue	[10, -50]		
YK	84	yellow-green	[-10, 20]		
		blue	[0, -30]		
YH	84	original point	[-5, 5]		

Note. For hiragana-color synesthete, only high-density region were described.

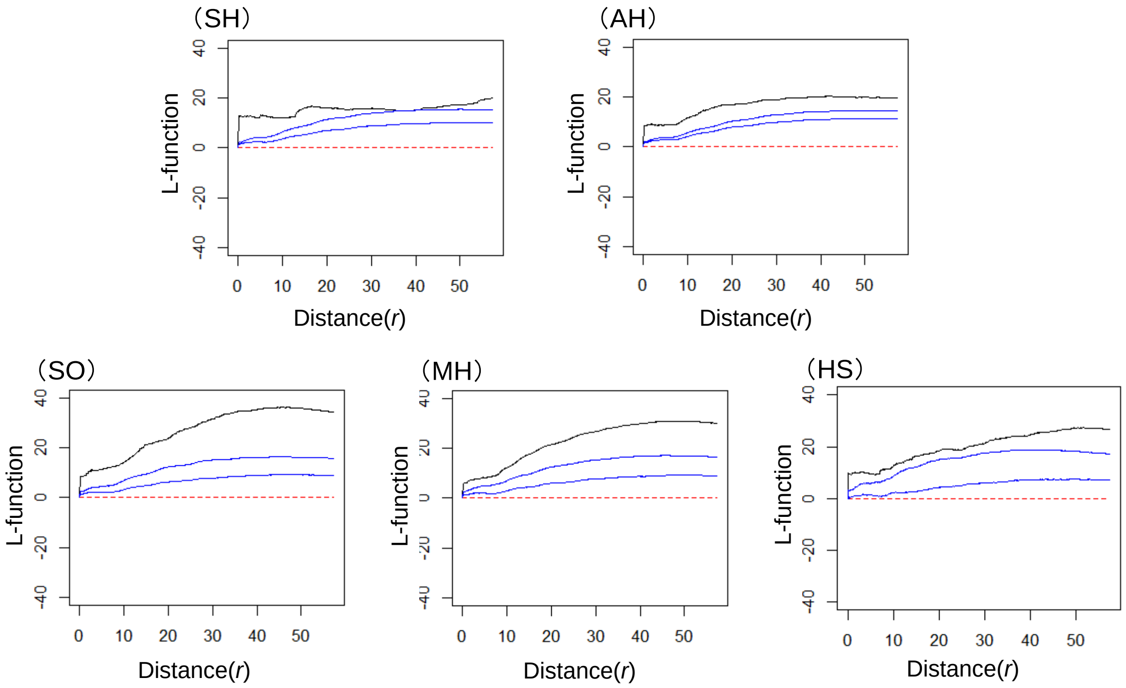


Figure 11. L-function of the point pattern for the chromatic synesthetic colors at distance *r* of a given point for kanji-color synesthetes. The solid black line indicates the computed L-function. The interval between the two blue lines indicates the 95% confidence intervals. Specifically, many spatial point patterns (1000) randomly selected from the Munsell renotation data can be generated under CSR and Ripley's K-function estimated for each one.

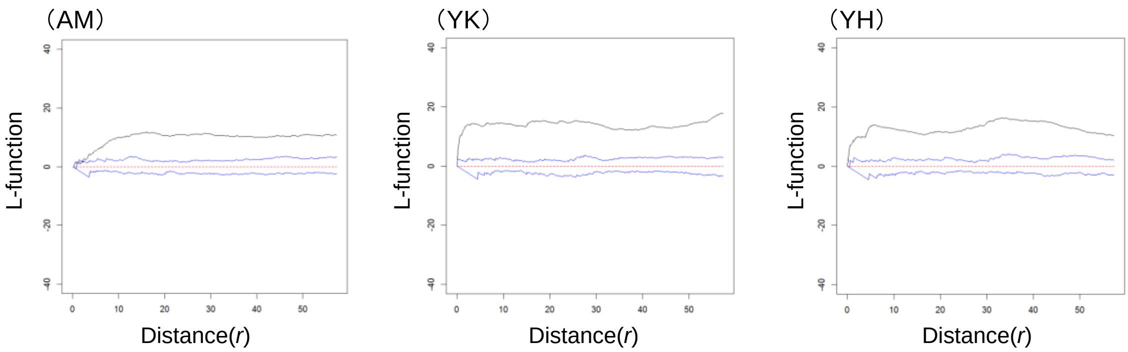


Figure 12. L-function of the point pattern for the synesthetic colors at distance *r* of a given point for hiragana-color synesthetes, in similar fashion to Fig. 11. The interval between the two blue lines indicates the 95% confidence intervals for complete spatial randomness (CSR). Specifically, many spatial point patterns can be generated under CSR and Ripley's K-function estimated for each one.

Explanations of the script for spatial statistics of synesthetic colors

Since the database was made in the widely used Excel format, it can be easily imported to many kinds of statistical software. For example, the above spatial statistics analysis was done using R, as is shown in Fig. 13. The details of the analysis steps are explained below to help researchers understand and modify the script for their own use.

Step 1: Prepare a *spatstat* package and input row data into R. Then, the user can input a portion of the database as a text file, for example, the L*a*b* coordinates of synesthetic colors.

Step 2: Create a point pattern object using a class *ppp* object. The *ppp(x, y, window = w, marks = mf)* will create the point pattern inside a rectangle. *x* (a*) and *y* (b*) are vectors of each coordinate of data points. The *window = w* specify a range of the polygon. Each coordinate value of the polygon was decided by each of most achromatic color (red: [a*, b*] = [82.28, 22.42]; green: [-139.00, 20.36]; yellow: [11.91, 134.92]; blue: [-14.69, -67.01]; purple: [116.06, -94.45]) from the Munsell renotation data (http://www.rit.edu/cos/colorscience/rc_munsell_renotation.php). Next is defining *marks*, which is an additional attribute of each point in the point pattern (Baddeley, 2010). For example, in addition to the color coordinates of synesthetic colors, a user could also record the kanji, hiragana, katakana, letter, and numerals. This marked point pattern is constructed by the *mf* in the script.

Step 3: Plot the point patterns and its density map. First, the user can plot the point patterns using a *plot(x, window = w)*, and the *x* is a point pattern. Next, a user can plot the map of kernel density estimation by a *plot(density(x, σ)*. The *x* is a point pattern. The *σ* is standard deviation of the isotropic Gaussian smoothing kernel used for the kernel method.

Step 4: Analyze point patterns using the L-function. The user can compute the K-function for a point pattern *x* using the *Kest* function. Next, the K-function can be used to plot the computed L-function using *plot(K, sqrt(iso/pi) ~ r)*.

Step 5: Analyze two types of point patterns by the cross L-function. The user can compute the cross-type between all pairs of types simultaneously using a command *alltypes(x, fun=”K”)*. The *x* is the marked point pattern. The *K* is the K-function. The example of two types of point patterns (katakana vs. hiragana) for synesthete SH was shown in Fig. 14

```
# ScriptSpatStat.R
rm(list=ls()) # remove all the variables from the workspace
print_on <- 1 # print on/off
library(spatstat)
#-----    input
cspace1 <- "L" # axis of luminance
cspace2 <- "a" # axis of red and green
cspace3 <- "b" # axis of blue and yellow
subject <- "Data" # name of subject
cspace <- sprintf("%s%s%s", cspace1, cspace2, cspace3) # "Lab"
fn <- sprintf("%s_%s%s", subject, cspace, ".txt") # name of data file
# scolors3D: standard data frame for 3D color coordinates
scolors3D <- read.table(fn,    header=FALSE, sep=",") # read "data_Lab.txt"
names(scolors3D) <- c(cspace1, cspace2, cspace3) # "L" "a" "b"
```

Step1
Load required packages and reading row data into R

```
# SpatStat's marked point pattern objects
# marks: categorical; Kanji, hiragana, katakana alphabet or digit
x <- scolors3D[[2]] # x coordinates of the points of the pattern
y <- scolors3D[[3]] # y coordinates of the points of the pattern
xrange <- c(-100, 100) # vectors of length x
yrange <- c(-100, 100) # vectors of length y

m <- 1:1229; # number of all data
for (i in 1:1085) m[i] <- c("kanji") # kanji
for (i in 1086:1141) m[i] <- c("hiragana") # hiragana
for (i in 1142:1193) m[i] <- c("katakana") # katakana
for (i in 1194:1219) m[i] <- c("alphabet") # alphabet
for (i in 1220:1229) m[i] <- c("digit") # digit
mf=factor(m) # a vector of the same length as x and y
levels(mf) # check that the factor levels are as you intended
# specify the window
w <- owin(poly = list(x = c(-14.69306841, 116.063891, 82.28463313, 11.90915956, -138.9965256),
  y = c(-67.00573254, -94.4521156, 22.42358507, 134.9172171, 20.35588592)))
mpp_Hi <- ppp(x, y, window = w, marks = mf) # create marked point pattern
ppa_Hi <- split(mpp_Hi)$alphabet;
ppd_Hi <- split(mpp_Hi)$digit
pph_Hi <- split(mpp_Hi)$hiragana
ppk_Hi <- split(mpp_Hi)$katakana
ppj_Hi <- split(mpp_Hi)$kanji;
ppad_Hi <- superimpose(pph_Hi, ppk_Hi) # hiragana & katakana
as.data.frame(mpp_Hi)
```

Step2
Defining marks and creating a point pattern object

```
par(mfrow=c(2,2))
plot(ppad_Hi, xlim = xrange, ylim = yrange) # distribution of hiragana & katakana
axis(1, pos = 0, labels = FALSE)
axis(2, pos = 0, labels = FALSE)
plot(mpp_Hi, xlim = xrange, ylim = yrange) # marked point pattern
axis(1, pos = 0, labels = FALSE)
axis(2, pos = 0, labels = FALSE)
if (print_on) { dev.copy2eps(file="Data_RawScatterPlot.eps") }
plot(density(pp_Hi, sigma = 8.46)) # map of kernel density estimation
if (print_on) { dev.copy2eps(file="Data_RawDensityPlot.eps") }
```

Step3
Plot point patterns and The map of kernel density estimation

```
## ----- Analyses #----- For pooled data
Ksc_Hi <- Kest(pp_Hi) # estimate its K function
# plot as the L function defined in shimatani's review # L:= sqrt(K/pi)-r
par(mfrow=c(1,1))
plot(Ksc_Hi, cbind(sqrt(iso/pi) - r, 0) ~ r, ylim = c(-40, 40)) # the plot of the L function
# monte-carlo test; 1% level
# NULL hypo: Poisson null, i.e., CSR (Complete Spatial Randomness)
Esc_Hi <- envelope(pp_Hi, Kest, nsim = 39, rank = 1)
print(Esc_Hi)
plot(Esc_Hi, sqrt(hi/pi)-r ~ r, col = "blue", ylim = c(-40, 40), add = T)
plot(Esc_Hi, sqrt(lo/pi)-r ~ r, col = "blue", ylim = c(-40, 40), add = T)
if (print_on) { dev.copy2eps(file="Data_LfuncWithEnvelope.eps") }
```

Step4
Analyze point patterns based on the distance by means of L function in classification.

```
# cross K function
KCsc_Hi = alltypes(mpp_Hi, "K") #compute the cross-type between all pairs of types
Kkh_Hi=KCsc_Hi[5,3] # katakana vs. hiragana
# monte-carlo test # NULL hypo: , Poisson null, i.e., CSR
Ekh_Hi <- envelope(mpp_Hi, Kcross, nsim = 39, i = "katakana", j = "hiragana")
par(mfrow=c(2,2))
# plot as the cross L function
plot(Kkh_Hi, cbind(sqrt(iso/pi) - r, 0) ~ r, ylim = c(-40, 40))
plot(Ekh_Hi, sqrt(hi/pi)-r ~ r, col = "blue", ylim = c(-40, 40), add = T)
plot(Ekh_Hi, sqrt(lo/pi)-r ~ r, col = "blue", ylim = c(-40, 40), add = T)
if (print_on) { dev.copy2eps(file="HiragaAll_LCrossfuncWithEnvelope1.eps") }
```

Step5
Analyze two types of point patterns by means of crossL function

Figure 13. Sample R script of our analysis of spatial statistics. Step 5 is described for further analyses of dependency of two point patterns.

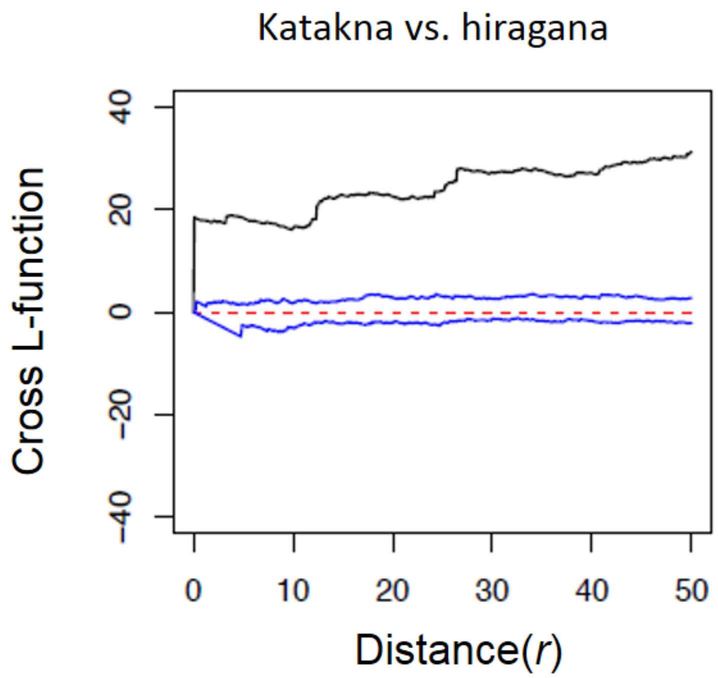


Figure 14. Cross L-function of two types of point patterns for the chromatic synesthetic colors for synesthete SH. The interval between the two blue lines indicates the 95% confidence intervals for complete spatial randomness (CSR).

DISCUSSION

All previous studies on grapheme-color synesthesia have considered dozens of samples per synesthete (often 26 Latin letters and 10 Arabic numerals). In this study, we created a new database, which we call the Japanese KANJI-Synesthetic Colors Database (K-SCD). The K-SCD has 1229 and 2349 synesthetic colors for each of two synesthetes associated with 483 kanji, 46 hiragana, 46 katakana, 26 Latin letters, and 10 Arabic numerals, 429, 325 and 191 synesthetic colors for each of three synesthetes, and about 80 synesthetic colors for each of three synesthetes associated with hiragana, Latin letters, and Arabic numerals. To our knowledge, no study collected such a large number of synesthetic colors per synesthete. The large samples in the K-SCD should allow investigation of the intrapersonal structure of the grapheme-color synesthetic experience and possibly lead to promising new ways of studying synesthesia.

We illustrated two such ways here. Although these are preliminary studies in the sense that only partial information from the database was utilized, they nevertheless provided important findings. The first example, taking advantage of the multidimensional properties of kanji, analyzed the regularity in the first- and the second-order relationships between the radicals of kanji characters and their associated synesthetic colors. This analysis found that the radicals with similar shapes to katakana characters have similar colors to those katakana characters. This second-order relationship suggests that the colors associated with certain kanji may originate from those associated with katakana. This possibility is consistent with a previous finding (Asano & Yokozawa, 2012) showing that synesthetic colors for Japanese graphemes acquired at an early age (i.e., numerals, hiragana, and katakana) affect those acquired later in life (i.e., kanji) via their phonological and/or semantic content. The present result suggests the possibility that visual shape also contributes as a key factor for the process of synesthetic learning. Future studies may find other factors by analyzing auxiliary information such as pronunciation, meaning, and grade level of kanji.

In the second application of K-SCD, we investigated the distribution of synesthetic colors in a*b* chromaticity space to understand the global structure of synesthesia. The spatial statistical analysis revealed that the synesthetic color distribution was neither random nor uniform. Instead, synesthetic colors formed multiple clusters that were separated each other in a*b* chromaticity space. This result corroborates a previous similar finding (Yamamoto, 2009) in hiragana, Latin letters, and Arabic numerals. Why did these synesthetic color clusters emerge? We conjecture that some kinds of first-order relationships first determine the core colors of clusters in early synesthetic learning and then second-order relationships such as those based on similarity determine the synesthetic colors of newly learned graphemes. In the second process, a new character may be tinged with a color similar to the core color of the character to which it is most similar, and the color distance from the core may be proportional to the distance in similarity between the two characters in a given grapheme space, leading to clustering. In this scenario, the synesthetic color clusters may reflect both between- and within-category difference in the grapheme similarity space.

The emergence of the synesthetic color clusters may be further analyzed using the cross L-function to investigate the interdependency of two point patterns. Point patterns can be divided into three categories: independent, attractive, or repulsive (Fig. 1: bottom). Our above hypothesis predicts the attractive dependency between kanji and hiragana characters and between kanji characters across learning grades. This is supported by our preliminary analysis for the inter-relation between hiragana characters and Latin letters (Yamamoto, 2009). A preliminary analysis for kanji among learning grades (sample codes are shown in Fig. 9) also supports this hypothesis.

In conclusion, the K-SCD provides researchers with a variety of information of regarding synesthetic color associations and enables novel research directions. The database, taking advantages of the multidimensionality of kanji characters and the abundance of possible samples, will be beneficial in developing our understanding of synesthesia. The database will be updated continually, when new data from new synesthetes and synesthetic color associations is obtained or when room for improvement is found.

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