A Colorful Report: Color Associations in Synesthesia

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Abstract

In recent years, academic research on synesthesia, a curious neurological condition, has gained popularity again. Most studies are focusing on its biological evidences, common characteristics and general trends over a population. However, individual special cases are often ignored, in spite of the fact that *diversity* is one important feature of synesthesia. In this report, we carry out case studies of three participants having color-related synesthesia. By presenting the details of their experiences and analyzing numerical data, we illustrate the uniqueness of their "settings", and investigate the underlying principles beneath their coloring schemes. Several key findings are: special lighting and pattern properties, categorization of colors, and localization of colors over color space. We also discuss the concept of "absolute color", synesthesia and qualia, and the origin of synesthetic colors.

Keywords: Synesthesia/synaesthesia; Grapheme–color; Sound–color; Visual system; Color constancy; Lightness constancy; Qualia

1. Introduction

1.1. What is Synesthesia?

Synesthesia, a somewhat uncommon word, comes from the Greek roots "*syn*" (union) and "*aisthesis*" (sense), literally means "union of senses". This word may refer to some multi-sensory metaphors in literature, or colorful interfaces used in media technology (like the fancy effects in Windows Media Player), but in the world of neuroscience, synesthesia is an actually existing neurological condition, which has many interesting and yet to be explored qualities.

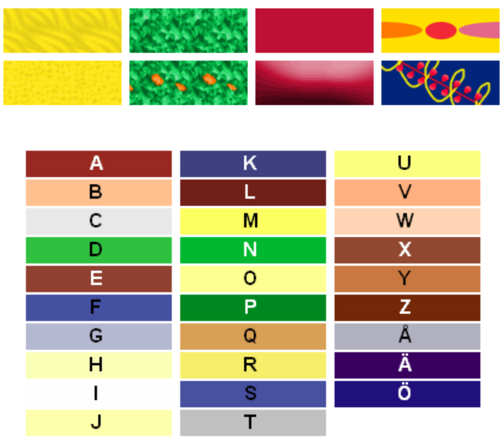


Figure 1: The colorful world of synesthesia. Color printing is recommended for this report.

A simple definition of synesthesia is "stimulations of one sensory module cause involuntary, automatic experience in another sensory module" (Cytowic, 1998). A person having synesthesia, called a *synesthete*, will have two or more of his/her senses (like vision, hearing, taste, touch, etc) interconnected together. Here are some examples. As descried in Cytowic's book *The man who tasted shape* (Cytowic, 1998), when Michael is tasting some foods or drinks, he could feel geometrical shapes like "points" or "smooth spheres" on his skin and fingertips. Daniel Tammet, an autistic savant portrayed in the UK documentary *The Boy With The Incredible Brain*, could see colored three-dimensional shapes when thinking of numbers, and the shapes fuse together when he does arithmetic calculations. For the three participants in this report, they could see colors when looking at a letter, thinking of a concept, or listening to a song (Figure 1).

In our everyday language, there are metaphors like "his mood is *blue* today", "the sound of horn is *sharp*". Or when you hear a fingernail scratching sound on a black board, you can feel a *pain* in your skin. However, synesthesia is an essentially different thing. What experienced by a synesthete is unique to the person, not common to all humans. Also, synesthetic experiences are not metaphors, but real neurological existence. This is demonstrated by various psychophysical experiments (Dixon *et al.*, 2000; Ramachandran & Hubbard, 2001a, 2001b; Smilek *et al.*, 2001), and recent brain imaging techniques (Paulesu *et al.*, 1995; Nunn *et al.*, 2002) which shows brain activity when synesthetic colors are experienced, much the same as when we see real colors.

For most people (non-synesthetes), this kind of phenomenon is exotic and hard to imagine. However, for the bearers themselves, it is just a natural part in their life. Their senses are connected since childhood, so without aware of a difference with other people, they often feel surprised when knowing other people do not have it, or even feel frustrated when is considered weird and talking about nonsense illusions.

Because synesthesia usually does not interfere with normal daily functioning, it is *not* considered as a mental disorder. Instead, many consider it as a gift, which is believed to increase creativity and artistic ability (Ramachandran & Hubbard, 2001b). The participants in this report are also able to take advantage of their connected senses to help in their study and career.

1.2. General Characteristics of Synesthesia

Synesthesia is believed to be a rare condition. Estimation of population differs in studies, ranging from 1 in 20,000 (Cytowic, 1989) to 1 in 20 (Galton, 1880), but a recent systematic study pointed out to be 1 in 1150 females and 1 in 7150 males (Rich *et al.*, 2005). Females are believed to have more chance to possess synesthesia (Baron-Cohen *et al.*, 1996; Rich *et al.*, 2005), but some argued that this is so only because females are more willing to tell others about their personal feelings. Also, synesthesia tends to occur in family (Galton, 1880; Baron-Cohen *et al.*, 1996), so it is not surprising that both participant S herself and her sister are synesthetes.

Synesthesia has several important characteristics: *automatic*, *involuntary*, and *consistent*. Whenever you ask a synesthete, he or she will tell you "I can't help, it just happens." The effects could not be erased or altered by one's own mind[1], and is automatically induced whenever a stimulus is presented. Moreover, since the childhood of a synesthete, the associations are retained all over his/her life. That means, if letter A is "dark unsaturated red", it would be always "dark unsaturated red". Tests and retests spanned through months or years confirmed this high consistency, where synesthetes could score up to 90% in the consistency of their color choice, whereas non-synesthetes could only have 30-40% of their colors matched in different trials (Baron-Cohen *et al.*, 1993).

On the other hand, synesthetic experiences are highly individualized, and could be drastically diverse among different individuals. This is one very important characteristic, *diversity*. For example, a synesthete Andy would say "number 7 has color of light green", while Brian would say "No, no… 7 should be shinny brownish-red!" Cindy may see the synesthetic colors "painted" onto the text she is reading, while Demeter may see the colors "insides her mind's eye".

1.3. Sub-types of Synesthesia

We use the terminology of Grossenbacher and Lovelace (2001), where the source stimulation (e.g. a musical sound) is called an *inducer*, and the evoked experience (e.g. color) is called a *concurrent*. Each sub-type of synesthesia can be interpreted as a mapping between an inducer and a concurrent, such as grapheme–color synesthesia means that letters and numbers (collectively called graphemes) evoke colors, or sound–touch synesthesia means that auditory stimuli trigger somatosensory sensations.

However, only some combinations of inducer—concurrent are common among synesthetes, like grapheme–color and sound–color are the most popular ones (Day, 2005). Some are just rare or even not yet recorded in literature. As color is the main focus in this report, here we list out the color-related sub-types.

- Grapheme–color (letters/numbers to colors)
- Time unit–color (weekdays/months to colors)
- General sound–color (e.g. alarm clock is blue)
- Musical sound–color (e.g. violin is red)
- Musical note–color (e.g. D# note is yellow)
- Phoneme–color (spoken words to colors)
- Taste–color; Smell–color
- Pain–color; Touch–color; Temperature–color; Orgasm–color
- Personality–color (see "auras" around people)

Other popular sub-types that are not related to colors:

- Number–spatial form (feel numbers as a time line)
- Time unit–spatial form (feel a week/year as a circle)
- Lexeme–taste (taste in words)

[1] Except some chemicals or drugs (e.g. coffee, alcohol) or mental condition (e.g. relaxed, focused) which could temporary enhance or diminish the strength of synesthesia (Cytowic, 1998)

- Grapheme–personality (e.g. letter A is shy, number 4 is lazy)

Synesthesia tends to exist in multiple flavors. If a person has one kind of synesthesia, he/she will be more likely to have the second and the third kinds, and so on (Ramachandran & Hubbard, 2001b). Indeed, a large portion of synesthetes have at least grapheme–color, time unit–color and/or sound–color, while in extreme case some even have up to ten different sub-types.

1.4. How Synesthetes See Colors?

In particular grapheme–color sub-type (letters and numbers evoke colors), if you ask a synesthete how he/she perceives their synesthetic colors, the answer would be difference from person to person. Some of them see the colors in an external space, such as projected onto the text itself, or projected on a screen (like "12 inch in front of me" (Ward *et al.*, 2006b)). Some see the colors in an internal space, so called "the mind's eye", or even merely know the colors but not seeing them. Dixon *et al.* (2004) proposed a classification called *projector-associator distinction*, in which the ones see colors in external space are called *projectors*, while the ones see in internal space or only know the color are called *associators*.

Ramachandran and Hubbard (2001b) have proposed another classification called *higher-lower distinction*. In case of *lower synesthesia*, colors are experienced whenever graphemes are actually seen on a screen or paper. This case is proved to be a true perceptual behavior by various psychophysical experiments (Dixon *et al.*, 2000; Ramachandran & Hubbard, 2001a, 2001b; Smilek *et al.*, 2001) instead of fabrication. In case of *higher synesthesia*, colors could be experienced by merely imagining the graphemes in mind, without any external visual aid.

Hubbard *et al.* (2005) suspected that the higher-lower and projector-associator distinctions are in fact the same thing, in a sense that a lower synesthete must be a projector, and a higher synesthete must be an associator. However, in a statistical study of Ward *et al.* (2006b), many of the participants have hybrid conditions, so the two classifications should be orthogonal to each other. This is consistent with our three participants, having different combinations of higher-associator, lower-associator, and lower-projector.

2. Motivation and Aim

In the early years of synesthesia research, researchers mostly relied on the faithful reports on individual cases. As early as the nineteenth century, Galton (1880) wrote an article in the magazine *Nature* about several interesting cases of visualized numerals, and opened the eyes of the scientific community to this remarkable phenomenon. In Alexander Luria's book *The Mind of a Mnemonist* (Luria, 1968), he examined Solomon Shereshevskii, a person with fascinating photographic memory and an extreme case of synesthesia interconnecting all of his senses (vision, hearing, touch, taste, smell, etc), for more then 30 years. And as mentioned earlier, Cytowic's description (1998) of a taste—shape synesthete in his book *The man who tasted shape* is also a very detailed individual investigation, which lead to some pioneering ideas in the field.

In recent years, researches changed their course to a more quantitative approach. Massive data collection and statistical methods are employed in hope of discovering some underlying principles. For example, Rich *et al.* (2005) investigated 192 grapheme–color synesthetes, and found some trends in their color associations (e.g. letter O is more likely to be white, and letter D is more likely to be brown). Nikolić *et al.* (2007) found that, after taking average of 19 synesthetes, there is a proportional relation between the usage frequency of a letter and the luminance of synesthetic color (e.g. letter E is the most frequently used letter, and has brighter synesthetic color in average, compare to rare letters like X and Z).

These quantitative studies could provide us an overall picture of the phenomenon. However, they often discard unusual data in flavor of statistical analysis. For example, in the research of Rich *et al.* (2005), responses such as "transparent color" or "clear color" are discarded. However, if you discuss with a synesthete, she will probably have her own story to tell, instead of just a list of color associations. There are often extra bits of information (e.g. participant K reported that "number 2 is dark pink, *but also a golden border, silver sparkles around, and turquoise flowing inside*") or many unexpected situations (e.g. participant B reported that "number 1 is not really a color *but a contrast between light and dark*"). These mind-blowing descriptions are often ignored and lost in the academic literature, and they are nevertheless valuable to the understanding of synesthesia itself, or even shed light on the understanding of how the human brain works.

Therefore, in this study, we will re-employ the old-style method – individual case studies. Together with numerical analysis on individual data, we hope to find some remarkable but rarely documented aspects in synesthesia.

3. Materials and Methods

We recruited participants who have at least one sub-type of color-related synesthesia. They are either acquaintances of the researcher, or made contact from the internet forum in Swedish website *Synestesi.se*.

We had several interviews with each of the participants, taking notes of their synesthetic experiences. The information gathered includes:

(1) General information – Such as how did they learn about their synesthesia, how it helps or troubled in their daily life.

(2) List of color associations – Which grapheme or sound is related to which color. Selected portion of the lists will be presented as tables and color lists in this report.

(3) Qualities of color associations – Such as how the colors are experienced, how strong are the associations, or any extra properties like transparency and textural patterns.

The following sections describe the participants and how we gathered the information from them.

3.1. Participants

There are three participants in the current study. All are Swedish citizens, one male and two females. As agreed with each of them, the information gathered in interviews could be published in this report, and no personal specific information will be disclosed.

Note that all of them use the Swedish alphabet, which is basically English alphabet plus three Swedish letters Å, Ä, Ö. The term “Roman alphabet” is used here in contrast to the Greek alphabet.

B, Swede, male, right-handed
Occupation: university student
Sub-types: grapheme–color (Roman alphabet, digits, higher numbers), time unit–color, pain–color, other special kinds of concept–color associations.
Classification: Higher (evoked by concepts), Associator (colors seen internally in mind’s eye)

K, Swede, female, right-handed
Occupation: university student
Sub-types: grapheme–color (Roman alphabet, digits), time unit–spatial form, other sound related associations.
Classification: Lower (evoked by perception), Associator (colors seen internally in mind’s eye)

S, Swede, female, left-handed
Occupation: university student and photography assistant
Sub-types: sound–color, color–sound, personality–color.
Classification: Lower (evoked by perception), Projector (colors seen externally at a position behind the eyes)

3.2. Gathering the General Information

Firstly, a listed of general questions about synesthesia are formulated, as shown in Appendix A. We then discuss with the synesthetes in face-to-face interviews, email conversations or MSN chats. Responses to the questions provided more understanding of their particular conditions, their similarity to common synesthesia characteristics or how they differ from them. Also, the responses allowed us to narrow down the following part of questions, i.e. knowing which sub-types could determine which kind of data list to be collected.

3.3. Gathering the List of Color Associations

Lists of color associations were obtained from the participants as raw data for further analysis.

The inducing stimuli are graphemes, abstract concepts, and sounds. Graphemes were drawn or printed on a paper or computer screen, but the participants could choose to imagine them, in case the colors induced were more vivid. Concepts were imagined in mind. For audio stimuli, musical instruments and human singing voices were provided by playing songs in MP3 format using Windows Media Player. The participant was free to repeat any part of the song to get enough stimulating, and earphones were

Figure 2: The color palette booklets: Pantone® Color Formula Guide (left), Repro Farveskala (center), Methuen Handbook of Colour (right)

used to minimize environmental noise. On the other hand, human speaking voices and other sounds are widely available in the environment.

The induced concurrents are colors, patterns and other additional properties. For colors, we provided two different ways for participants to choose the best matching ones. One is the color palettes booklets, which provide a handy and realistically feeling color palette. Another one is the computer program ColorPicker, which provide an interactive color choosing environment. Participants K and S prefer the former way, while participant B prefers the later.

3.3.1. How to Specify Colors

A color could be specified by wordings like "blue" or "dark saturated blue", as used in most studies of synesthesia. However, to be more precise for analysis, numerical value will be a better choice.

A *color model* is a mathematical representation of colors, where each color can be specified as a set of three or four numbers. RGB, CMYK, HSV, and CIE-L*a*b* color models are the ones used in this report. RGB model, the most well-known in computer technology, represents each color as red (R), green (G) and blue (B) values (all have range 0 to 255). For example, a particular blue could have RGB value (25, 30, 200). CMYK model is mostly used in printing industry, with cyan (C), magenta (M), yellow (Y), and black (K) values (all have range 0-100). HSV model has values in hue (H, range 0-360), saturation (S, range 0-100), and value/brightness (V, range 0-100). CIE-L*a*b* model is less common but nevertheless useful, with values in luminance (L*, range 0-100), blue-yellow hue (a*, range about -100 to 100), and green-red hue (b*, range about -100 to 100). For how to convert values between color models, see Appendix B.

3.3.2. Color Palette Booklets

We provided several choices of the printed color palette booklets, as shown in Figure 2.

Pantone is a widely used, proprietary color system used in design and manufacturing industries. We use one of their booklet *Pantone® Color Formula Guide (Solid Matte)* which provides 1,114 color choices, more or less in order of hue and brightness. Each color has a Pantone color code (e.g. "212C") printed on the booklet, from which the corresponding values in RGB, HSV and CIE-L*a*b* color models can be obtained using Adobe Photoshop "color libraries" function. This booklet provides a wider range of selectable colors (especially the vivid ones) then the following two palettes, but is less organized.

Repro Farveskala is a book with colors indexed with different combinations of cyan (C), magenta (M), yellow (Y), and black (K) in the CMYK color space. The choice of colors is restricted by the CMYK printing method.

Methuen Handbook of Colour is a book with colors indexed in three dimensions: hue (each page), intensity (each row), and tone (each column). Each color has a code (e.g. "21A8"). Again, the choice of colors is restricted by the CMYK printing method.

The color palette booklets have advantages of being easy to use and allowing to compare among colors, but have disadvantages of restricted color choices and subject to different lighting conditions (such as lighting color and reflection, as seen in Figure 2). To cater this lighting problem, we employ soft sunlight or white lights as possible when using the color books.

The color codes obtained were converted to HSV value, and then recorded in raw data table. If a synesthetic color is described as in-between two colors from booklet,

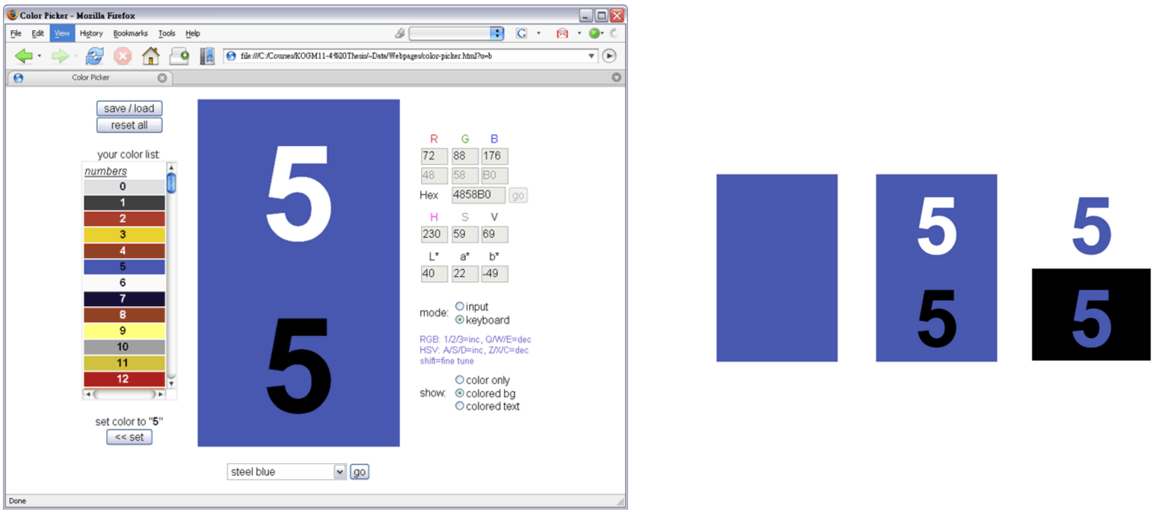


Figure 3: (Left) Interface of the ColorPicker program. (Right) Its 3 viewing modes – color only, colored background, colored text.

average is taken in the HSV values, or if it is a modification of a color from booklet (e.g. "Pantone 5807C but lighter"), corresponding adjustment is made to the HSV values.

3.3.3. Computer Program – ColorPicker

A computer program called *ColorPicker* was developed to run on internet browsers (Microsoft Internet Explorer or Mozilla Firefox). See Figure 3 for its screenshot.

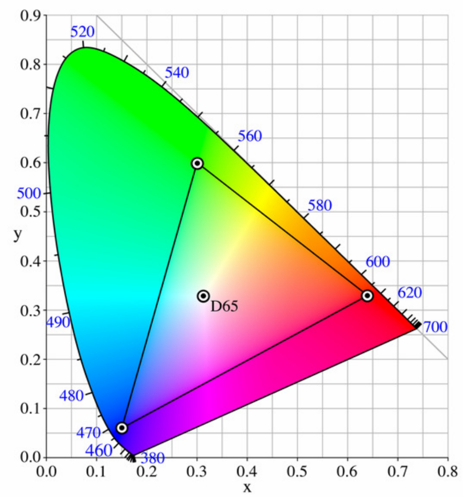


Figure 4: Color range provided by sRGB color space (the triangle) within CIE 1931 color space (the horseshoe shape, gamut of human vision).

A color rectangle is displayed at the center of program, for which the participant can adjust its color by pressing keys on the keyboard (e.g. press the Q key to increase red in RGB, press the Z key to increase hue in HSV). After the participant was satisfied with the adjusted color, he/she could save it to the color list, and finally the list of RGB color data was sent to the researcher.

The color rectangle can be displayed in three modes: color only, colored background with white/black text, or colored text with white/black background. The participant might find it more convenient to match colors in a particular viewing mode.

The computer program used on a computer screen has advantages of allowing to choose most colors (as in the sRGB color space, see Figure 4), allowing fine tune of colors, and the participant can use it at home. Disadvantages are that operations need learning, and some computer monitors (especially the LCDs of laptop computers) shows varying colors in different viewing conditions, as reported by participant B.

3.4. Gathering the Quality of Color Associations

During the phase of gathering color associations list in the last section, the participants were asked for any extra properties for the colors, such as any special patterns and if the association is too weak. Some of the special patterns are hard to be explained by the participants, and in this case, metaphors or illustrations might be used. The questions are also listed in Appendix A.

3.5. Analysis of Data

In order to discover any underlying relationship among color data, we convert the first-hand color values (usually RGB or Pantone color code) into other color models, then use Microsoft Excel to analyze and plot graphs. It turns out that HSV and CIE-L*a*b* color models are the most useful ones, where we can observe the grouping and distribution of colors respectively.

4. Results

Each of the participants shows a very unique profile of his/her synesthesia. B is special in having colors for many kinds of concepts (e.g. mathematics), together with the lighting properties in his colors. K has several graphemes associated with dynamic and even artistic patterns. And what make S unique is her bi-directional connection between hearing and color vision, but with different settings.

In this section, results and analysis will be presented participant by participant.

Firstly in the *raw data part*, the list of color associations, as well as any special properties and exceptional cases (marked as *blue italic*) are shown in table format. "Color description" column is either the original wordings from the participant, or a color name added by the researcher. "Color (HSV)" column has the values of color hue (H, range 0-255), saturation (S, range 0-100), and value/brightness (V, range 0-100).

Also included are colored illustrations, which could give a more intuitive feeling of their colorful universe.

Following that is the *description part*, showing general characteristics and qualities as described by the participant. Finally in the *analysis part*, we give deeper observations and analysis on the information collected.

4.1. Participant B

B has color associations with a wide range of inducers. Common types are numbers, Roman alphabet, weekdays and months; uncommon types are Greek alphabet, mathematical concepts, countries, and other concepts.

4.1.1. Raw Data from B

Color data are collected from various email conversations and interviews. Those collected in the earliest days (e.g. mathematical concepts, countries) are only color names, thus without numerical values. Later ones are collected with the computer program ColorPicker.

To compare the data from two different environments, colors of weekdays are collected twice with ColorPicker. Time 1 was 24-Feb-2008, performed in my laptop computer (which he commented that the LCD monitor tends to be bluish) at a public library with bright lighting. Time 2 was 3 days later, 27-Feb-2008, performed in his computer at home with dim lighting.

Numbers

Inducer	Color description	Color (HSV)
0	*Light contrast*	-
1	*Dark contrast*	-
2	Brownish red	8, 73, 65
3	Quite saturated yellow with some hints of brown	52, 79, 90
4	As color 2 (brownish red) but darker and more brown	12, 77, 56
5	Blue but somewhat darker and less saturated than pure blue	230, 59, 69
6	White or slightly off-white towards brown-orange	60, 0, 98
7	Dark blue, almost black	250, 73, 23
8	As color 2 (brownish red) but more towards brown and somewhat less saturated	18, 72, 58
9	Pale but distinct yellow	60, 49, 100
10	*Black or contrast*	-
11	*Metallic* yellow with hints of grey	53, 69, 81
12	As color 2 (brownish red) but less saturated	0, 81, 69
13	Varying, but usually like color 11 (*metallic* yellow) but with more red	24, 71, 87
14	Varying, but often close to color 4 (brownish red) or color 7 (dark blue)	12, 71, 43
15	Almost saturated blue	240, 75, 75
16	White	0, 0, 97
17	Black or possibly very dark blue	270, 100, 12
18	Varying, but often like a pale version of color 8 (brownish red)	12, 53, 81
19	Like color 9 (pale yellow) but less saturated	60, 30, 100
20	Like color 2 (brownish red) but lighter and somewhat more red	0, 83, 75
24	Brownish red	14, 89, 59

Inducer	Color description	Color (HSV)
30	Pale yellow	56, 61, 97
40	Brownish red	16, 88, 53
50	Blue	243, 81, 69
60	Light gray	0, 0, 87
70	Black	0, 0, 0
80	Brownish red	15, 80, 62
90	Pale yellow	63, 49, 100
100	Brownish red	15, 50, 25
500	Darker blue	240, 100, 50
1,000	White	0, 0, 97
1,000,000	Dark yellow	50, 100, 75
1,000,000,000	Very dark blue	264, 100, 15

Roman alphabet

Inducer	Color description	Color (HSV)
A	Brownish red	4, 78, 59
B	Something in between pink and orange	25, 43, 100
C	Light gray	0, 0, 90
D	Unsaturated green	126, 75, 75
E	Reddish brown	10, 66, 56
F	Unsaturated blue	232, 57, 62
G	Pale blue-gray	231, 13, 81
H	Pale brownish yellow	64, 27, 100
I	White	0, 0, 99
J	Pale yellow	60, 32, 100
K	Dark blue	238, 51, 50
L	Dark red	5, 78, 43
M	Slightly unsaturated yellow	60, 62, 100
N	Green	135, 100, 72
O	Pale yellow	61, 43, 100
P	Unsaturated green	134, 100, 53
Q	Orange-brown	34, 61, 84
R	Yellow	56, 57, 96
S	Blue	234, 55, 62
T	Gray	0, 0, 75
U	Pale yellow	61, 49, 100
V	Pink with a little bit of orange	22, 49, 100
W	Pink	25, 29, 100
X	Orange-brown	15, 66, 56
Y	Brownish orange	24, 68, 78
Z	Brown with hints of orange	17, 93, 45
Å	Unsaturated violet-blue	240, 8, 75
Ä	Dark violet-blue	276, 100, 37
Ö	Dark blue, almost black	248, 87, 48

Weekdays (time 1)

Inducer	Color description	Color (HSV)
Monday	Brownish red	10, 87, 43
Tuesday	Brownish yellow	38, 96, 62
Wednesday	Light blue	222, 54, 100
Thursday	Dark blue	253, 100, 12
Friday	White	210, 4, 81
Saturday	Gray	24, 3, 52
Sunday	Black	240, 100, 6

Weekdays (time 2)

Inducer	Color description	Color (HSV)
Monday	Brownish red	15, 80, 62
Tuesday	Brownish yellow	55, 100, 84
Wednesday	Light blue	229, 18, 100
Thursday	Dark blue	240, 100, 31
Friday	White	240, 5, 100
Saturday	Gray	0, 0, 81
Sunday	Black	270, 100, 12

Months

Inducer	Color description	Color (HSV)
January	White	240, 6, 97
February	Light blue-gray	21, 100, 62
March	Red towards orange	104, 73, 81
April	Green	230, 54, 69
Mat	Blue	65, 30, 100
June	Pale yellow	62, 62, 100
July	Yellow	18, 80, 62
August	Brownish red	100, 20, 94
September	Pale green	42, 58, 75
October	Black or dark red, quite vague	58, 50, 94
November	Brownish yellow	240, 6, 97
December	Vague, possibly black or dark contrast	240, 9, 34

Greek alphabet

(Only those used in mathematics and physics)

Inducer	Color description (most my wordings)	Color (HSV)
α (alpha)	Brownish red	11, 100, 65
β (beta)	Pink	20, 51, 90
Γ (capital gamma)	Dark gray *with lack of light*	0, 0, 25
γ (gamma)	Light gray	0, 0, 65
Δ (capital delta)	Black	-
δ (delta)	Green	120, 100, 62
ε (epsilon)	Brown	21, 100, 53
ζ (zeta)	Dark gray	0, 0, 31
η (eta)	Like N (green), but darker as *affected by xi* (symbols learnt at the same time)	120, 50, 37
Θ (capital theta)	Light gray	0, 0, 75
θ (theta)	Light gray	0, 0, 94
ι (iota)	White	0, 0, 100
κ (kappa)	Dark blue	240, 69, 40
Λ (capital lambda)	Dark gray	0, 0, 37
λ (lambda)	*Slightly glowing* light brown	22, 82, 72
μ (mu)	*Slightly glowing* light yellow	60, 55, 98
ν (nu)	Light brown	22, 70, 84
Ξ (capital xi)	Dark brown	0, 100, 37
ξ (xi)	Black	0, 0, 0
ο (omicron)	light yellow	63, 30, 100
Π (capital pi)	Brownish yellow	51, 72, 90
π (pi)	Brownish yellow	45, 71, 87
ρ (rho, density)	Green	132, 100, 62
ρ (rho, radius)	Brownish yellow	51, 78, 87
Σ (capital sigma, sum)	Brown	28, 100, 59
Σ (capital sigma, variable)	Dark blue	240, 71, 43
σ (sigma)	Light grayish blue	240, 15, 59
τ (tau)	Dark gray	0, 0, 37

Inducer	Color description (most my wordings)	Color (HSV)
υ (upsilon)	Light brown	33, 75, 75
Φ (capital phi)	Black	0, 0, 0
φ (phi)	Light gray	0, 0, 81
χ (chi)	Black	0, 0, 0
Ψ (capital psi)	Brown	27, 100, 62
ψ (psi)	Light brown	32, 84, 81
Ω (capital omega)	Gray	0, 0, 56
ω (omega)	Pink	12, 62, 100

Mathematical concepts

Inducer	Color description
+ (plus)	*Dark contrast*
- (minus)	*Light contrast*
∫ (integral)	*Black or dark contrast*
Σ (summation)	Dark red
* (multiplication asterisk)	Nothing or a darker and *transparent* version of color 11 (yellow)
× (multiplication cross)	Like "*" (*transparent* yellow) or close to color 4 (brownish red)
· (multiplication dot)	Black or color 7 (dark blue)
× (vector cross product)	Brownish red
/ (division)	Nothing or color 7 (dark blue)
= (before proven)	White
= (after proven true)	Black
≠ (inequality)	Black or reddish dark brown
π (pi)	Very close to Tuesday (brownish yellow)
sin (sine)	White
cos (cosine, earlier understanding)	Similar to pi (brownish yellow) but darker
cos (cosine, deeper understanding)	Pale blue with a little bit gray
tan (tangent)	Black
hyperbolic function	Brownish yellow
$\mathcal{B}$, $\mathcal{H}$, $\mathcal{L}$, etc (calligraphic letters denoting sets)	*Darker version of the letter itself*

Measurement-related concepts

Inducer	Color description
Time	White
Positive infinity	Brownish orange
Negative infinity	Light contrast
Future (short term, positive)	Vague, possibly yellow
Future (long term, problematic)	Light blue
Future (sci-fi way)	Grayish blue, *metallic surface diffusing light*
Past	Vague, possibly pale green
History	Possibly brown
Now	Yellow
Tomorrow	Vague, possibly pale yellow
Early	Brown or no color
Late	Brownish red
Second	Unsaturated dark blue
Minute	White
Hour	Vague, possibly pale brownish yellow
Day	No color
Month	Brownish yellow
Year	Vague, brownish orange or black
Meter	Brownish yellow or contrast
Distance	Pale green or contrast

Elementary particles (in physics)

Inducer	Color description (my wordings)	Color (HSV)
Electron	Blue	253, 69, 81
Positron	Reddish pink	356, 79, 75
Proton	Pink	10, 55, 81
Neutron	Gray	0, 0, 72
Neutrino	Light gray	0, 0, 90
Anti-neutrino	Gray	0, 0, 80
Muon	Dark blue	250, 66, 56
Higgs-boson	White	0, 0, 100

Chemical elements

Inducer	Color description (my wordings)	Color (HSV)
H (hydrogen)	Light pink	20, 33, 97
He (helium)	Pink	7, 49, 100
Li (lithium)	Light gray	0, 0, 84
C (carbon)	Gray	0, 0, 62
N (nitrogen)	Green	124, 62, 75
O (oxygen)	White	0, 0, 100
F (fluorine)	Blue	231, 53, 81
Ne (neon)	Light yellow	60, 18, 100
Na (sodium)	Yellowish green	101, 100, 81
Si (silicon)	Dark yellow	53, 69, 81
P (phosphorus)	Green	124, 59, 69
S (sulfur)	Dark yellow	49, 73, 94
Cl (chlorine)	Light grayish blue	240, 16, 100
Ar (argon)	Dark pink	7, 57, 87
K (potassium)	Dark blue	253, 65, 62
Ca (calcium)	Light gray	0, 0, 97
Kr (krypton)	Dark purple	260, 75, 50
Xe (xenon)	Light pink	20, 40, 94
Cs (cesium)	White	0, 0, 100
Rn (radon)	Light green	138, 71, 87
U (uranium)	Green	105, 72, 69
Pu (plutonium)	Dark blue	240, 100, 56

Countries

Inducer	Color description
Sweden	No strong color
Denmark	White
Norway	Dark red
Finland	Light blue
Iceland	Vague, possibly white or gray
Britain	White or pale orange
England	Dark red
Scotland	No strong color, possibly brownish yellow
Wales	Dark blue or gray
Spain	Yellow
France	Orange-brownish yellow
Germany	Dark blue or no color (after learnt more, color association decreases)

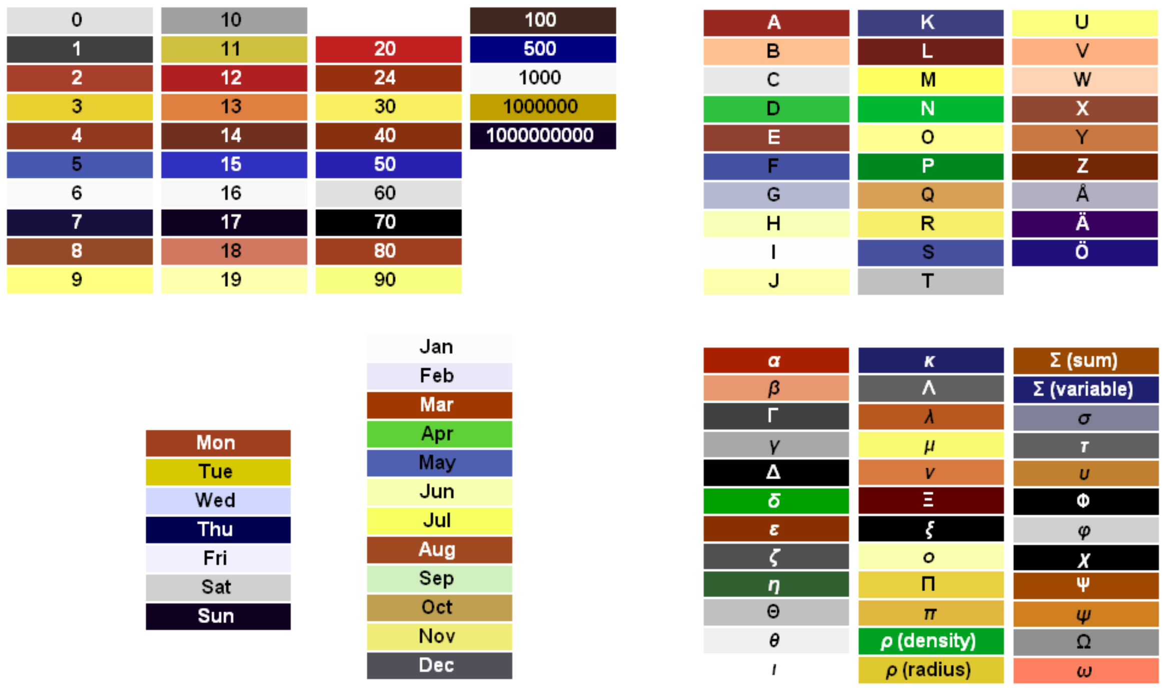


Figure 5: B's colors for various inducers: numbers, weekdays, months, Roman alphabet, and Greek alphabet.

Inducer	**Color description**
Poland	Grayish light blue
Italy	Brown
USA	Red
Mexico	Orange
Russia	No strong color, possibly green
Ukraine	Yellow
Turkey	Brownish yellow
Kazakhstan	Dark brown
Mongolia	Brownish yellow
China	Yellow
Vietnam	White or light grey
Thailand	Dark grey or dark contrast
Philippines	White or pale green
Japan	Black or dark blue
India	Brown
Pakistan	Dark green
Afghanistan	Vague, dark red
Australia	Brownish orange

Different versions of his own name

Inducer	**Color description**
When first learned his name	Dark blue
When inner changes in life	Dark blue
When considering his shyness	Salmon pink/orange
When things go as planned but not very interesting	Blue with violet mixed
When many things happening at the same time	Black

4.1.2. Description of B's Synesthesia

General characteristics

There are several interesting characteristics in B's color-related synesthesia, as the followings.

His synesthetic colors are very subtle and not salient in his conscious, as he "usually doesn't think about it". Due to this, he needs much effort or "mental power" to think about the colors. Indeed, it took many rounds to complete the long color lists above, only being exhausted after thinking hard.

Although being subtle, the effect is clear when individually colored digits or letters appear in "wrong colors", for example if a letter blue to him is printed in red. In relation to this, B is often particular or even picky in matching the colors. When using ColorPicker, several factors such as quality of computer screen, viewing angle to the screen, or even different portion of the screen could drastically affect his choices.

The colors usually come from the concept behind, not the physical perception of a word. However, he could switch among different association levels. For example "ONSDAG" (Swedish word for Wednesday), when focusing on the concept (Wednesday), the synesthetic color is blue, association is stronger; when focusing on the word itself ("ONSDAG"), the color is a mixture of yellow (letter O) and red (letter A), i.e. emphasis on the vowels, association is weaker; when focusing on individual letters, each color is just the same as in Roman alphabet.

The synesthetic colors are sometimes ambiguous, varying or could switch between totally different colors, especially in the case of mathematical concepts. This often resulted from multiple concepts behind an inducer, e.g. number 13 could be similar to color of 3 (the usual case) or color of 8 (when thinking 13 as 8 + 5). More examples are given in the following sub-sections.

Lighting properties are prominent additional features to many of his colors, e.g. metallic, transparent, and "contrast". They are further discussed in each sub-section.

Numbers

Normally in grapheme–color synesthesia, colors only apply to digits 0 to 9, but in B's case, the higher numbers also have colors. However, the digits 0 to 9 have stronger associations, while higher numbers usually got their color from lower number counterparts.

As also noticed by B himself, the colors are correlated in certain ways, such as similarities among various digits and among different number series. This will be further explored in the analysis part.

Note that numbers 0, 1 and 10 are not colors but "contrast" as described by B. It is a very vague experience, and is almost impossible to explain in simple words. Several attempts using metaphors like "left and right visual fields seeing a light color and a dark color simultaneously", "a shallow drawn 0, with white (light) inner and black (dark) border", "a transparent ink-like liquid allowed to see through", or as the illustration shown in Figure 6. B also ranks their transparency as 0 the most, 1 the least, and 10 in between.

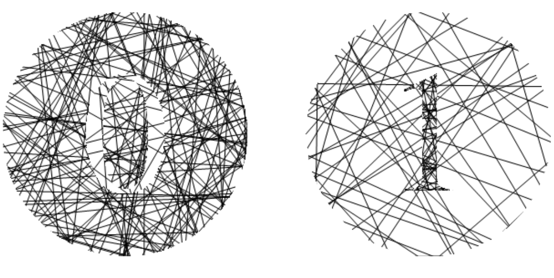


Figure 6: "Light contrast" and "dark contrast" for numbers 0 and 1 as illustrated by B.

Also, the metallic color of number 11 is described as a brass surface (alloy of copper and zinc) reflecting light, possibly due to association with an analogue clock with brass surface.

Roman alphabet, weekdays and months

In contrast to numbers and concepts, B's colors for Roman alphabet, weekdays and months are quite normal as other synesthetes, without showing any special properties.

There is no difference between capital and small Roman letters, as well as in different font types.

Note that for weekdays and months, B can switch colors among concept level, word level and letter level, as the example "ONSDAG" in General Characteristics section above.

Greek alphabet and mathematical concepts

B's colors are the most complicated for mathematical concepts, including the Greek letters, but are also the most vague and uncertain. In several occasions, he expressed a difficulty ("it is hopeless") to explain what he experiences.

His colors of Greek letters do not come from the Greek language as he did not learn the language itself, but are strongly related to their usage in mathematics and physics. That is why some of the Greek letters have more than one color when associated with different concepts.

Note the special lighting properties, such as glowing colors of small letters lambda and mu, "contrast" of addition and subtraction, transparent color of multiplication, and "lack of light" of capital letter gamma.

There is even more complicated color blending effects for the mathematical concepts, especially when different symbols are combined or form an equation. For example, "2π" has a color between 2 and π; the hyperbolic sine function "sinh()" has both color of sine (white) and hyperbolic (brownish yellow) activated, but mixed together; the fraction "2/3" is "some kind of connection between color 2 and 3, and is darker" because of division, which is dark blue in color.

Also, several concepts can have more then one versions. For example, "equality" have different colors when before or after the equation is proven; "cosine" has two versions, one is the earlier understanding as a simple function (using degree), and one is the deeper understanding (using radian), like inside equation $\sin^2 x + \cos^2 x = 1$.

Finally, to explain the occurrence of "contrast" in both numbers and mathematics, B noticed a grouping: number 0 and subtraction are related to the concept "emptiness", thus having "light contrast"; number 1, addition and integral are related to "fullness", thus having "dark contrast".

Other concepts and lists

B has colors for countries which are known to him, but not those unfamiliar to him like African countries, as well as water bodies like seas and lakes.

Note that he does not have a strong color association with Sweden, his home country. Instead, he has color associations with different provinces of Sweden. Also for Germany, which has a color before, but the color association turned weak after knowing more about the country.

Note the interesting color associations of his own name, with different life periods or viewing of himself. This maybe a special case of personality–color synesthesia.

4.1.3. Analysis of B's Synesthesia

Grouping of colors

We could find some trends and groupings in B's synesthetic colors, either already noticed by B himself, or arose when carefully comparing the data.

The most obvious trends could be found in the numbers, as illustrated in Figure 7.

As reported by B, there are relationships among lower numbers – (1, 7), (0, 10), (2, 4, 8), (3, 9, 11). These groupings could be explained by their underlying impressions, such as being odd out (1, 7), emptiness (0, 10), powers of 2 (2, 4, 8), and odd numbers (3, 9, 11). In contrast, 5 and 6 are quite distinct ones.

On the other hand, colors are similar within number series. 2, 12 and 20 are all brownish-red, 5, 15, 50 and 500 are blues from pale to saturated. That means the colors of numbers are grouped by their *principle digit*. We define *principle digit* as the most important digit in synesthetic coloring of numbers, for example, 5, 15, 50 and 500 all

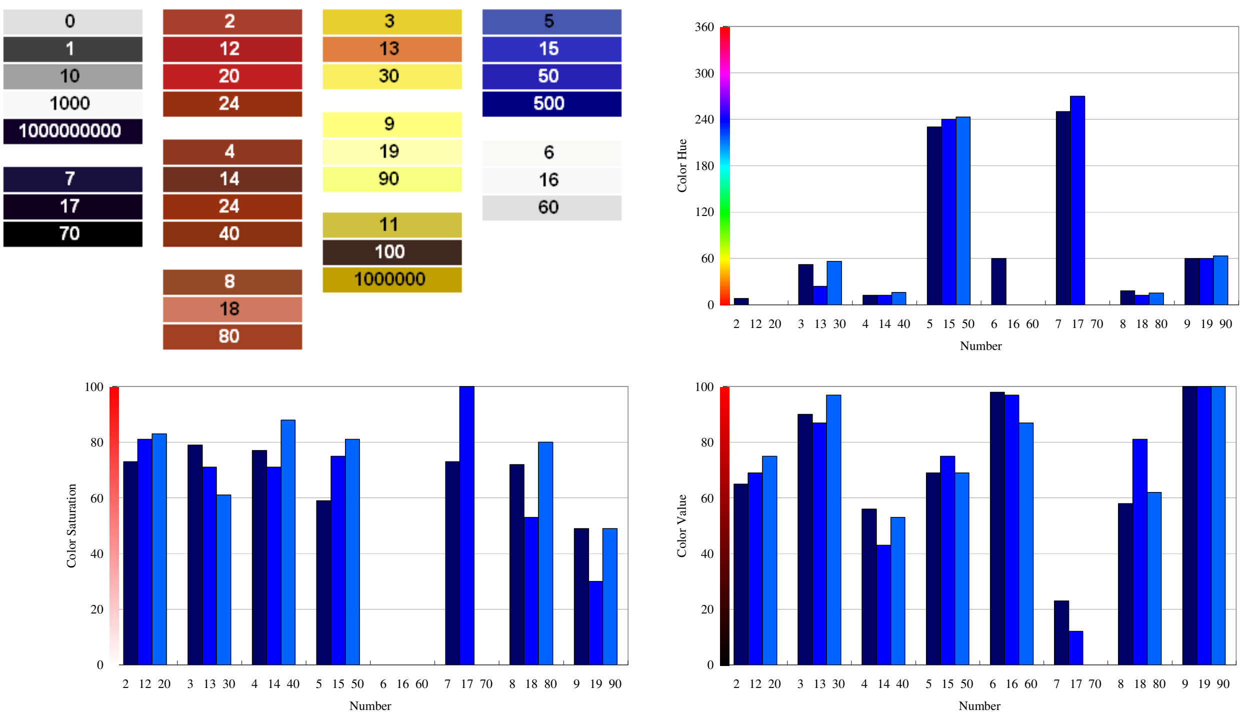


Figure 7: B's colors for numbers, grouped by principle digit (upper left), and their component analysis in color hue (upper right), saturation (lower left), and value/brightness (lower right).

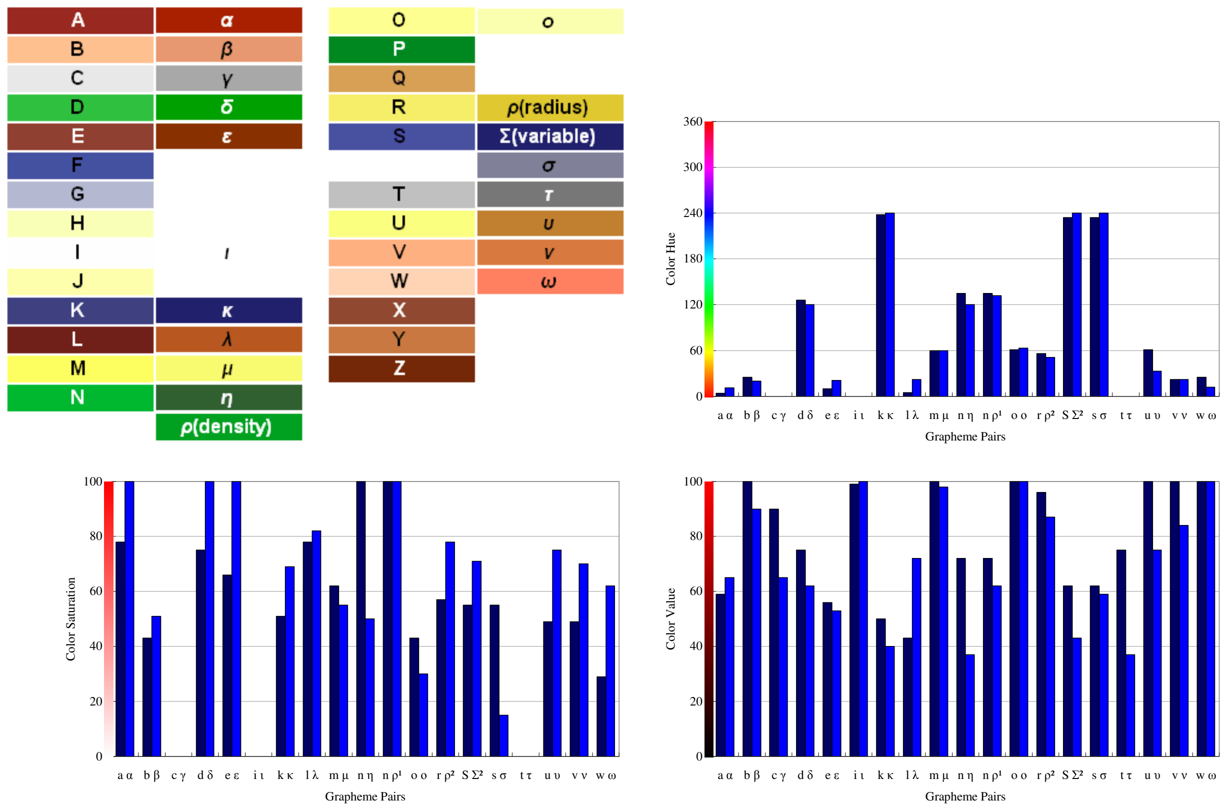


Figure 8: Comparison of B's colors for Roman and Greek alphabet (upper left), and their component analysis in color hue (upper right), saturation (lower left), and value/brightness (lower right).

have principle digit 5. This is consistent with our arithmetic understanding (15 is 10 + 5, 50 is 5 × 10), and also their naming in Swedish and English ("fifteen" and "fifty" derived from "five", or in Swedish, "femton" and "femti" derived from "fem").

To be more quantitative, we plot graphs with respect to color hue, saturation and value/brightness in HSV color model. Since 0 and 1 are special cases, we only include the principle digits from 2 to 9. Resulting graphs are shown in Figure 7.

As seen in the graphs, color hues within a principle digit group are very close to each others. This confirms that the numbers are related in synesthetic experience.

There are no obvious trends in color saturation and value/brightness. However, as observed in the color blocks, higher numbers often have a more saturated or darker color then the lower counterparts, as in groups of 2, 5, 6 and 7.

Similarly, we find similarities between Roman and Greek letters. Some are related by linguistic correspondence (e.g. alpha to A, delta to D), some are by visual appearance (e.g. eta to N, nu to V, omega to W).

We plot the three graphs in Figure 8. Again, color hues are very close between Roman and Greek counterparts. For color saturation and value/brightness, most of the cases are that Greek letter has more saturated and darker color (e.g. alpha, beta). In a few cases, oppositely, the Greek letter has less saturated and lighter color (e.g. lambda, mu), which may due to their glowing effect.

In conclusion, inducers related to each other often have very close color hue but deviated color saturation and value/brightness. This is remarkable because B always use RGB model to adjust his colors, while still show a consistency in color hue after converting to HSV model, keep in mind that RGB and HSV models do not have simple relations in between.

This result could be compared with several existing theories. Beeli *et al.* (2007) found that graphemes with higher usage frequency (e.g. letter E) tend to have a higher luminance (i.e. higher color value/brightness). This could be applied to here that lower numbers and English letters are used more frequently compared to higher numbers and Greek letters, hence similar hue but higher luminance. On the other hand, Cohen Kadosh *et al.* (2007) found that within 0 to 10, larger numbers tends to have lower

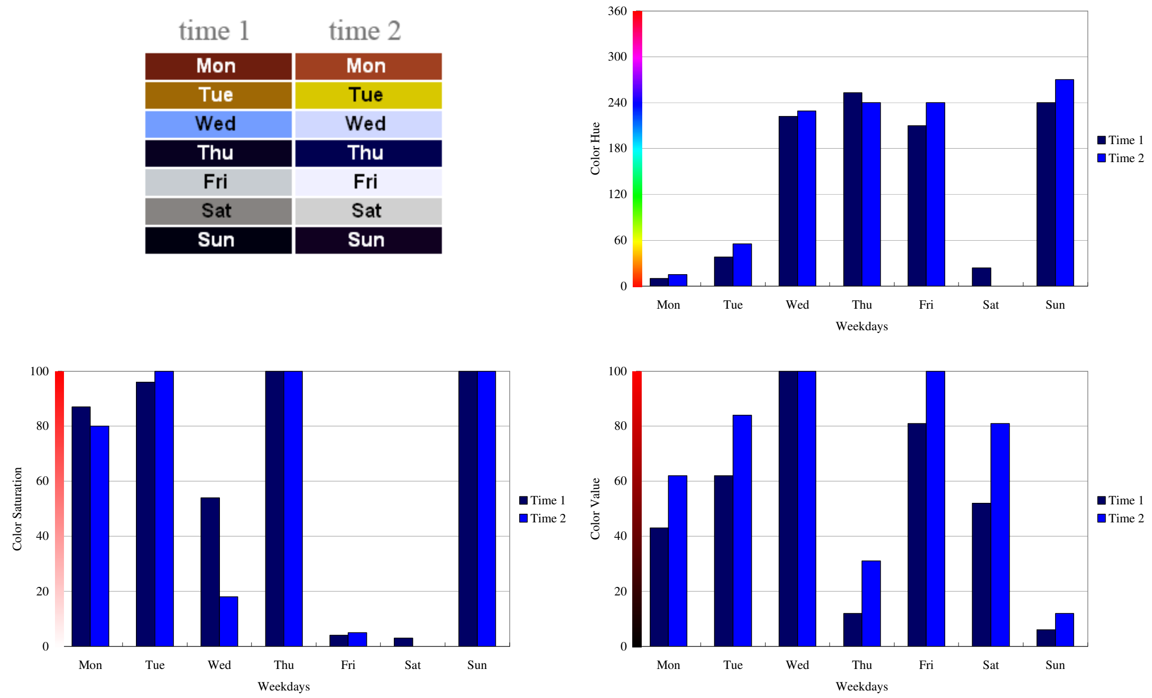


Figure 9: Comparison of B's colors for weekdays in two different environments (upper left), and their component analysis in color hue (upper right), saturation (lower left), and value/brightness (lower right).

luminance, consistent with our assertion that larger numbers with a principle digit group tends to be more saturated and darker.

Variations over environment

We could also study the color variations over different environments. Colors of weekdays are chosen in two environmental conditions – one is a somehow bluish computer screen in bright lighting, and one is another computer screen in dim lighting. Color hue, saturation and value/brightness are compared in graphs, as shown in Figure 9.

Here, we found that the participant tried to adjust the colors *in opposite* to the equipment and lighting conditions. Firstly, color in time 2 are more tends to blue (towards value 240), except Saturday and Sunday that they are grey and black, color hue is negligible. Secondly, colors in time 2 (in dim lighting) are constantly brighter then in time 1 (in bright lighting).

This counter adjustment is remarkable, and may led to a concept called "absolute color", as will be further discussed in General Discussions (section 5.5 - Sensitivity of color matching and "absolute color").

Distribution over color space

Among B's synesthetic colors, yellow, brownish-yellow

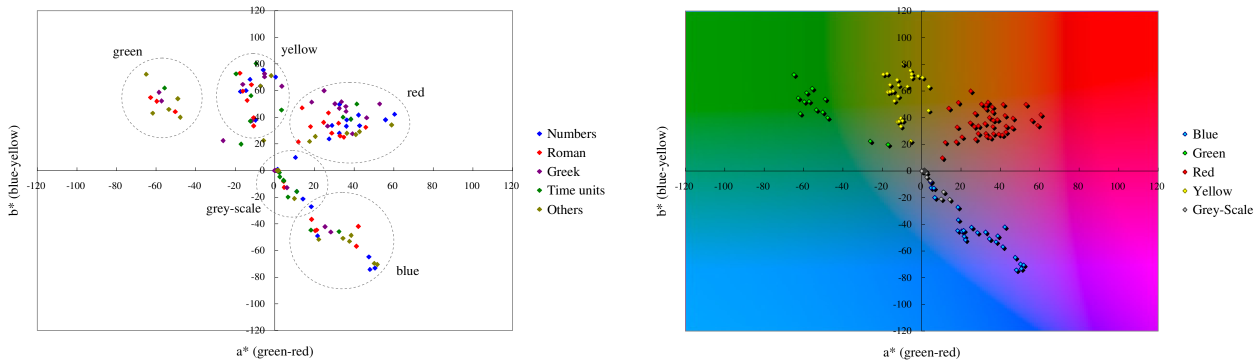


Figure 10: Distribution of B's colors in the CIE-Lab a × b* space, with data series in inducer type (left) and color type (right).*

and brownish-red are the most frequent ones, while blue and green are rarer, not to mention the absence of purple.

To investigate any trends in the overall color collection, we plot graphs with axes a* (determining blue-yellow hue) against b* (determining green-red hue) in CIE-L*a*b* color model. All colors listed in the raw data table having HSV value are included. Resulting graphs are shown in Figure 10.

The colors are obviously not scattered around but localized into several color groups. The most populous are the red and yellow groups, as observed in the raw data. Moreover, as in the left graph, there is no centralization in respect to the inducer types. Each inducer type (numbers, Roman letters, Greek letters, time units, and others) has colors from reds, yellow, blues, greens, and grey-scales, with a minor exception that numbers do not have greens.

This localization of colors could be explained by the fact that many colors are close together as the underlying concepts are correlated.

4.2. Participant K

K has grapheme–color synesthesia, which associates colors to digits and Roman alphabet.

She also has other sub-types of synesthesia, like time unit–spatial form (days in a week, or months in a year, is perceived as a three-dimensional ring in space), and many associations with sound (sound or music evoke motions, patterns or touch feelings), but are not included in this report.

4.2.1. Raw Data from K

We repeated the data collection in two separate interviews, in order to investigate the consistency or variations in her colors. One took place at 13-May-2008 (time 1), another one at 27-May-2008 (time 2), separated by 14 days. In time 1, color lists are collected in numerical (0-9) and alphabetical (A-Z) orders, while in time 2, colors are collected in random order. This is to minimize the chance of memorizing.

Numbers (time 1)

Inducer	Color description with Pantone color code	Color (HSV)
0	White	0, 0, 100
1	Black	0, 0, 0
2	Pink (212C) *with golden border, silver sparkles around, and turquoise (2995C) flowing inside*	Pink: 335, 68, 96 Turquoise: 195, 100, 88
3	Brown (470C)	22, 77, 62
4	Dark pink (7425C)	341, 78, 74
5	Bright yellow (109C)	49, 100, 100
6	Blue (286C)	219, 100, 65
7	Orange yellow (1225C)	42, 69, 100
8	Brownish red (1797C)	359, 80, 78
9	Turquoise (638C) *with silver sparkles*	191, 100, 84

Numbers (time 2)

Inducer	Color description with Pantone color code	Color (HSV)
0	White	0, 0, 100
1	Black	0, 0, 0
2	Pink (225C) *with golden border, silver sparkles around, and turquoise (306C) flowing inside*	Pink: 325, 82, 90 Turquoise: 191, 100, 89
3	Brown (1605C)	21, 80, 64
4	Dark pink (193C)	347, 89, 75
5	Bright yellow (123C)	44, 81, 100
6	Blue (294C)	214, 100, 47
7	Orange yellow (1235C)	41, 94, 100
8	Brownish red (193C)	347, 89, 75
9	Turquoise (312C) *with silver sparkles*	191, 100, 82

Roman alphabet (time 1)

Inducer	Color description with Pantone color code	Color (HSV)
A	Dark blue (540C)	207, 100, 35
B	Brown (470C)	22, 77, 62
C	Milky yellow (115C)	49, 74, 98
D	Orange yellow (1235C)	41, 94, 100
E	Light green (367C but softer)	88, 51, 84
F	Green (370C)	88, 76, 55
G	White	0, 0, 100
H	Light green (366C)	85, 38, 87
I	Black	0, 0, 0
J	Brown (470C)	22, 77, 62
K	Dark brown (4625C)	18, 67, 32
L	Vanilla (7499C but lighter), *filled inside a dark border*	60, 13, 100
M	Blue (2935C)	211, 100, 73
N	Blue (285C)	206, 100, 81
O	White	0, 0, 100
P	Orange yellow (108C)	51, 100, 99
Q	White	0, 0, 100
R	Milky yellow (113C)	50, 68, 98
S	Red (200C)	348, 92, 74
T	Black	0, 0, 0
U	White	0, 0, 100
V	Light brown (4645C)	24, 48, 69
W	Brown (4635C)	24, 60, 58
X	*Metallic* grey (411C)	15, 21, 36
Y	Grey (408C)	18, 11, 64

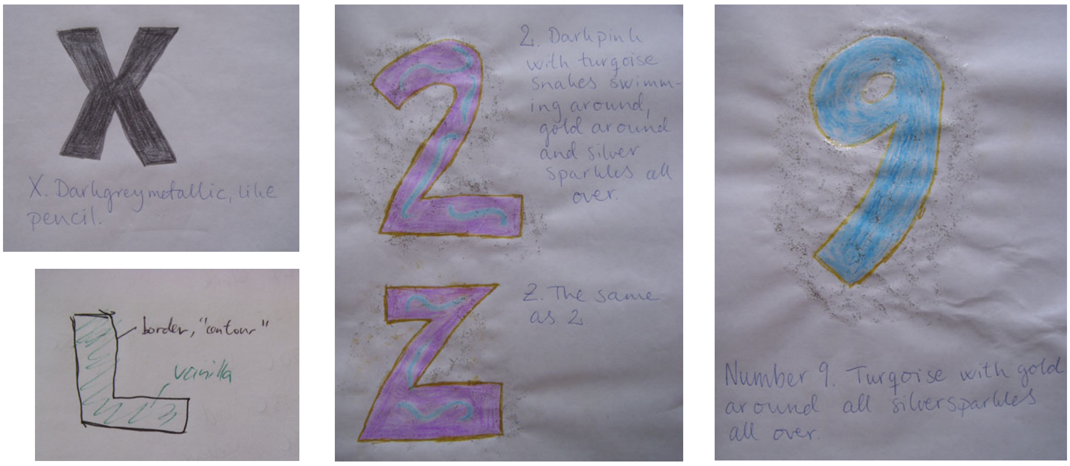


Figure 11: (Top) K's artistic depiction of some special graphemes, and my not-so-artistic depiction of her letter L. (Left) K's colors for Roman alphabet and numbers.

Inducer	Color description with Pantone color code	Color (HSV)
Z	Pink (212C) *with golden border, silver sparkles around, and turquoise (2995C) flowing inside*	Pink: 335, 68, 96 Turquoise: 195, 100, 88
Å	Dark blue (294C)	214, 100, 47
Ä	Dark blue (2955C)	206, 100, 41
Ö	White	0, 0, 100

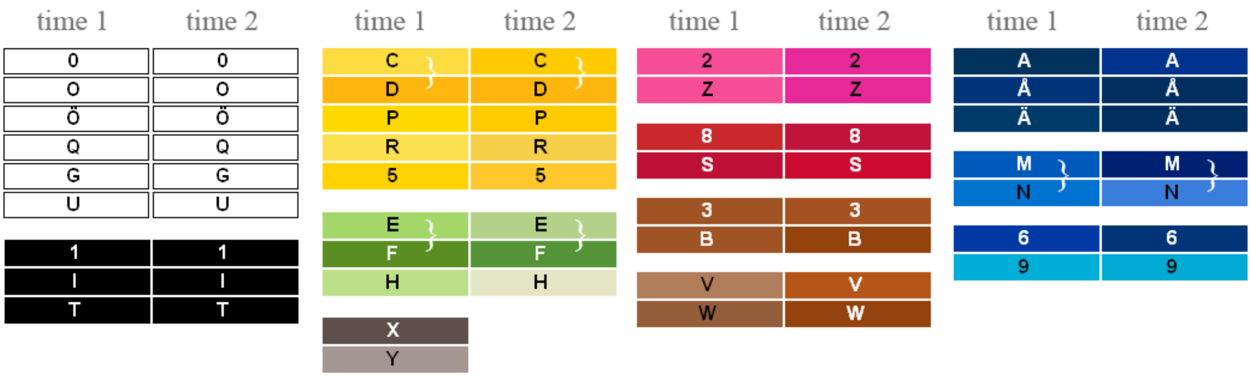
Roman alphabet (time 2)

Inducer	Color description with Pantone color code	Color (HSV)
A	Dark blue (287C)	218, 100, 55
B	Brown (1535C)	23, 90, 58
C	Milky yellow (116C)	47, 100, 100
D	Orange yellow (1235C)	41, 94, 100
E	Light green (between 577C and 366C)	84, 33, 81
F	Green (between 576C and 362C)	100, 61, 57
G	White	0, 0, 100
H	Light grey (5807C but lighter)	61, 13, 89
I	Black	0, 0, 0
J	- N/A -	-
K	- N/A -	-
L	- N/A -	-
M	Blue (2748C)	223, 100, 44
N	Blue (2727C)	214, 73, 85
O	White	0, 0, 100
P	Orange yellow (116C)	47, 100, 100
Q	White	0, 0, 100
R	Milky yellow (129C)	46, 71, 96
S	Red (186C)	349, 95, 80
T	Black	0, 0, 0
U	White	0, 0, 100
V	Light brown (471C)	23, 86, 71
W	Brown (1535C)	23, 90, 58
X	- N/A -	-
Y	- N/A -	-
Z	Pink (225C) *with golden border, silver sparkles around, and turquoise (306C) flowing inside*	Pink: 325, 82, 90 Turquoise: 191, 100, 89
Å	Dark blue (295C)	210, 100, 37
Ä	Dark blue (295C)	210, 100, 37
Ö	White	0, 0, 100

4.2.2. Description of K's Synesthesia

In K's synesthetic world, numbers and letters are not only colorful, but also pattern-rich. The most eye-catching pattern can be found in number 2 and letter Z, as depicted in Figure 11. In her words, both of them are "dark pink with turquoise snakes swimming around, gold around and silver sparkles all over". Similarly, number 9 is "turquoise with gold around and silver sparkles all over." In her depictions, silver sparkles are represented by glitter glue.

Several other letters are also special: letter X has a metallic feeling (represented by pencil texture), and letter L has a border filled with vanilla color.



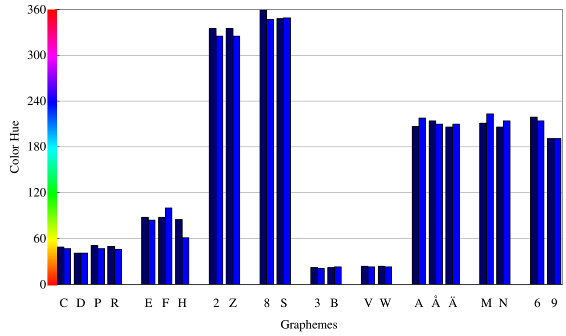
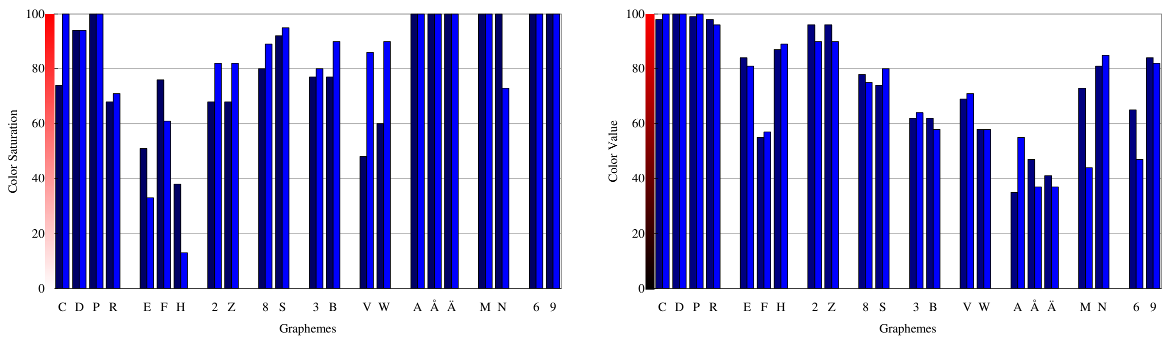


Figure 12: K's colors for numbers and Roman alphabet grouped by similarity, taken in two different dates (top), and their component analysis in color hue (middle right), saturation (lower left), and value/brightness (lower right).
"Buddies" pairings are indicated by parenthesis "}".



K could recognize several simple rules in her coloring scheme. Number 2 and letter Z have the same color and pattern because they have similar shapes; letters A, Å and Ä are just English letter A with different diacritics, thus all are blue; number 1 and letter I are black, number 0 and letters O, Ö are white, the reason is trivial. However, we found deeper relations behind the colors, which will be shown in the analysis part.

Curiously, K stated that there are several pairs of "buddies" in her alphabet. C and D are buddies, E and F are buddies, M and N are also buddies. The meaning of this pairing up is not clear, even from herself, but may be related to learning sequence.

4.2.3. Analysis of K's Synesthesia

Grouping of colors

By carefully examining K's color list, we could find more groupings other than the ones recognized by K, according to similarity in colors and shapes. The groupings are shown in Figure 12 (the color blocks on left).

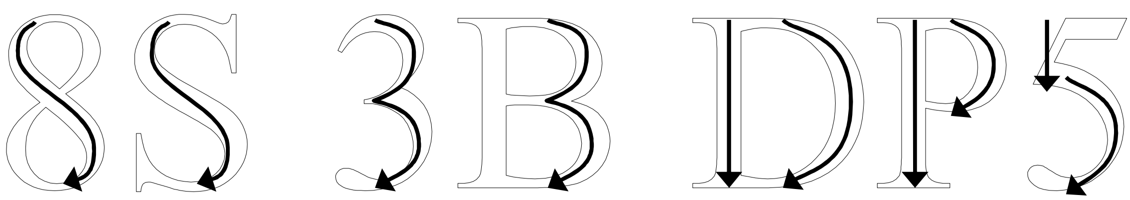


Figure 13: Similarity of stokes in K's grapheme groupings.

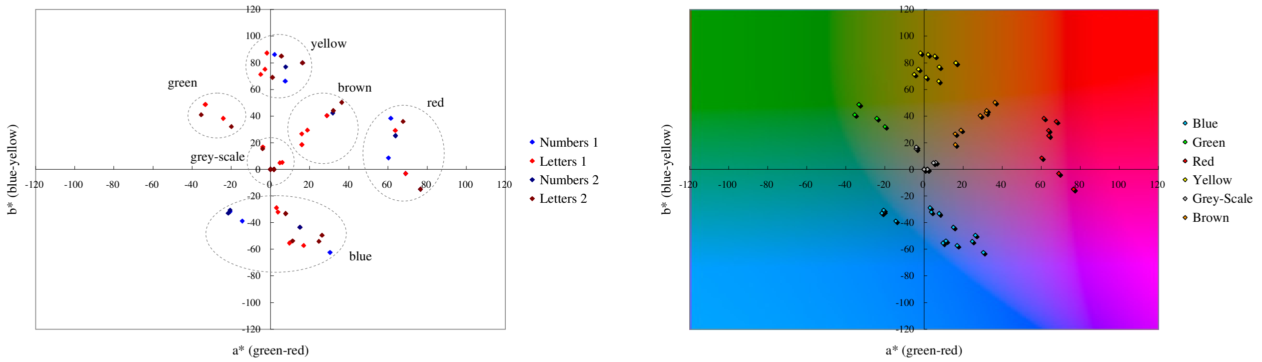


Figure 14: Distribution of K's colors in the CIE-Lab a × b* space, with data series in inducer type (left) and color type (right).*

We plot comparison graphs for the three HSV model components – color hue, saturation, and value/brightness respectively. See Figure 12 for the left (darker) bars in graphs. Although color saturation and value/brightness varies, color hues are very close in each group. This suggests that the groupings are reasonable.

An even closer look to the groupings, the similarity is not only about the visual shapes, but actually the *stroke orders* of the graphemes. As illustrated in Figure 13, the graphemes within a group have similar main strokes. They only differ in relative position of stokes or other minor strokes.

In particular, the groups are: (0, O, Ö, Q, G, U) having a circle/major arc; (1, I, T) having a dominant vertical; (D, P, R, 5) having a vertical then an arc (C is not the case but related due to "buddies" pairing); (E, F, H) having verticals and horizontals; (X, Y) having a crossing; (2, Z), (8, S) and (3, B) having Z-like, S-like and 3-like strokes respectively; (V, W) and (M, N) are doubles; (6, 9) are mirror images; (A, Å, Ä) are variations of letter A.

This connection with stroke orders possibly originated from the first time K learnt the numbers and letters – when the little girl held a pencil in her hand trying to draw the curves and lines, colors and patterns are also incorporated into the firing of neurons in the brain. These color groupings are like the "fossils" of the early learning process.

We will further discuss this point in General Discussions (section 5.3 - Origin of synesthetic colors).

Variations over time

Also in Figure 12, data collected from two time instances (time 1 and time 2, separated by 14 days) can be compared. Left-side blocks and bars are from time 1, while right-side ones are from time 2.

As usual, color hue is preserved. Value/brightness only has minor differences. The only prominent changes are in saturation, for example in (E, F, H) group, saturation is overall lowered by some amount, but in (V, W) group, saturation is overall heightened by some amount. This is not surprising, if considering the theory that colors are inter-related inside a grouping, but not over different groupings.

Distribution over color space

At first glance, K's colors consist of a wide spectrum, not biasing on certain hues.

We plot graphs with axes a* (determining blue-yellow hue) against b* (determining green-red hue) in CIE-L*a*b* color model, with all color data including the two time instances. Result is shown in Figure 14.

Localization could be observed in the graphs. Colors are centralized in several islands, such as yellows and reds/pinks.

4.3. Participant S

S has both sound—color and color—sound synesthesia, but with different associations and qualities. She also has personality—color associations, which is limited to the personalities of her close acquaintances. Here we only include data of her sound—color synesthesia, which has more persistent associations.

4.3.1. Raw Data from S

A few interviews are conducted to collect the sound—color data, by listening to songs and environmental sounds, or merely imagining the sounds.

Note: Color codes with plus (e.g. "2985C + 299C") means they co-occur for a stimulus, and with commas (e.g. "803C, YellowC") means a range of possible colors.

Musical instruments

Inducer	Color description with Pantone color code	Color (HSV)
Cymbal	Light blue (2985C + 299C)	194, 63, 91 196, 100, 87
Flute	Yellow (803C, YellowC), *with wavy or spotty pattern*	53, 89, 100 52, 100, 99
Chinese flute (Dizi)	Yellow *with orange dots under it*	-
Horn in general	Orange (Orange021C)	21, 100, 100
Bagpipe	Brownish orange (1525C + 1595C + 166C)	22, 100, 78 22, 89, 85 21, 99, 89
Strings in general	Red (200C) *with flat or three-dimensional structure*	348, 92, 74
Violin	Red (1795C but darker)	357, 83, 74
Piano	Red (185C)	347, 100, 90
Electronic piano	Red (485C)	3, 86, 86
Electronic Piano	Red (between 485C and 7417C)	358, 88, 89
Electronic flute	Red mixed with orange and yellow	-
Chinese strings (Guzheng)	Red (1788C) *with orange (Orange021C) hidden behind*	Red: 356, 82, 94 Orange: 21, 100, 100
Chinese strings (Guzheng)	Red (between 185C and 186C) *with yellow, purple and orange hidden behind*	347, 97, 84
Drums in general	Dark blue (2747C, 2748C, 280C, 2768C, 282C)	221, 100, 48 223, 100, 44 220, 100, 47 221, 82, 29 212, 100, 27
"Polluted" drums	Dark blue (2767C) *with black shadows*	214, 69, 28

Human voices

Inducer	Color description with Pantone color code	Color (HSV)
Speaking voice	Yellowish green (360C, 362C, 368C, 370C) *with texture of tree leaves*	114, 58, 75 115, 65, 60 95, 78, 73 88, 76, 55
Telling a lie	Grayish green (between 30B3 and 30C4 in Methuen)	70, 50, 58
Singing voice	Green (354C, 356C, 347C, 349C) *with texture of tree leaves*	142, 100, 68 147, 100, 47 148, 100, 60 155, 100, 41
Purple singing voice of some special singers	Purple (VioletC, 2607C)	262, 87, 62 275, 86, 47
Cass Phang	Green (356C) *with velvet feeling*	147, 100, 47
Chet Lam	Green (3405C)	156, 100, 67
Aiko	Green (354C)	142, 100, 68
Kiroro	Green (354C) *with orange dots on top (151C)*	Green: 142, 100, 68 Orange: 28, 100, 100
Kiroro & Aiko duo	Green (354C) *with orange dots on top (151C) and olive green (450C) in background*	Green: 142, 100, 68 Orange: 28, 100, 100 Olive green: 50, 53, 32
Cher	Purple (2617C) *with orange (1505C) dots*	Purple: 277, 84, 43 Orange: 26, 100, 100
Bonnie Tyler	Orange (between 1505C and 164C) *with purple (between 259C and 2592C) dots*	Orange: 22, 86, 100 Purple: 289, 73, 55

Other sounds

Inducer	Color description with Pantone color code	Color (HSV)
Playing plastic wrapping of a brand of instance noodle	Playing different parts of the wrapping give: *Red (032C) at center, pink (7423C) going from right, orange (151C) going from left, yellow (YellowC) in background*	Red: 356, 83, 95 Pink: 344, 54, 89 Orange: 28, 100, 100 Yellow: 52, 100, 99
Moving furniture	Brown (4625C)	18, 67, 32

4.3.2. Description of S's Synesthesia

Interestingly, S has both directions of synesthesia between hearing and color perception. The sound—color synesthesia is more apparent, as she could always see the colors whenever hearing a sound, but the color—sound one only occasionally happens, and only for a large homogenous area of the same color.

The two channels, as S stated, have "different settings". If a sound triggers a color, this color would not trigger the same sound. One example is the sound of cymbal in a drum set gives light blue color, but a light blue wall in turn

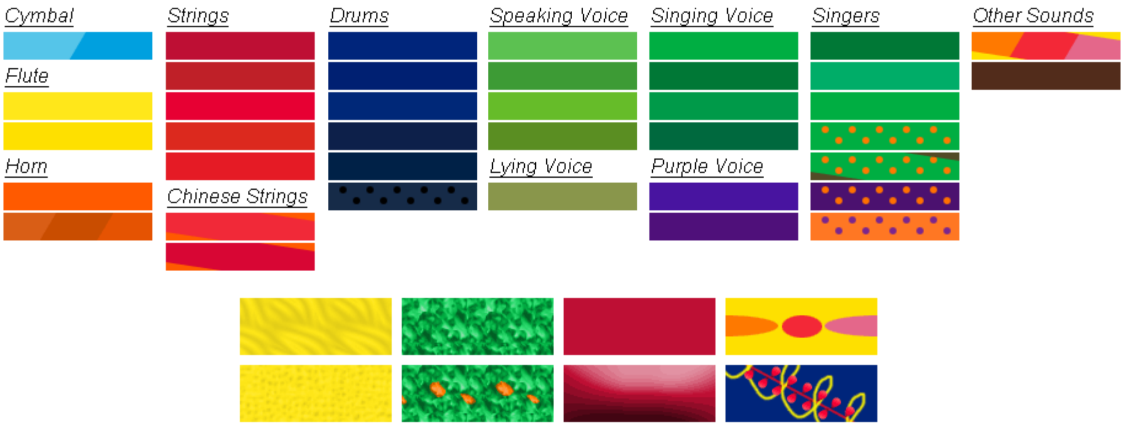


Figure 15: (Top) S's colors for different sounds, including musical instruments, human voices and others. The listing is in the same order as in raw data tables. (Bottom) My depiction of some color patterns, based on her descriptions. Note that these are depictions only, not the experiences themselves.

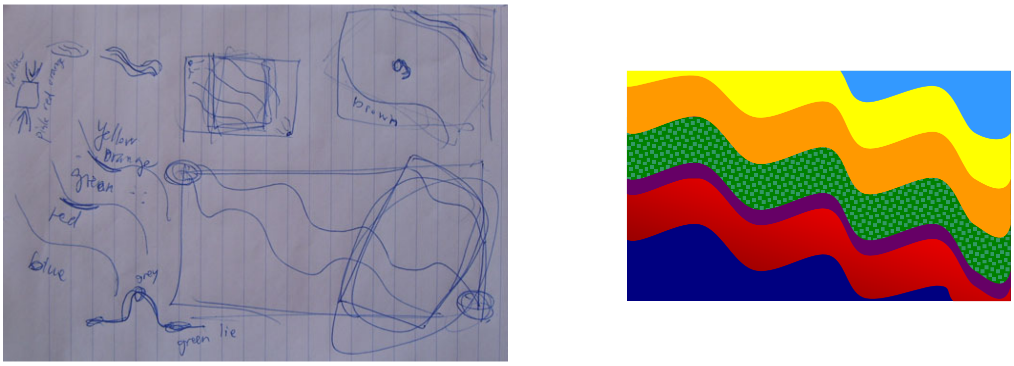


Figure 16: (Left) S's explanation of how she perceives the colors – color streams flowing from lower-right to upper-left of visual field, and "zooming" ability. (Right) Order of the color streams. Note that not all colors will appear at the same time.

(occasionally) produces a kind of "ding-ding" sound[2].

S can perceive the colors in her visual field, but unlike most projector cases, it is projected at a screen *behind* her eyes. The colors form wave like streams, originated from the lower-right corner and ended at the upper-left corner, as shown in Figure 16. Different color streams occupy different horizontal bands, from top to bottom: light blue (cymbals), yellow (flutes), orange (horn-like), green (human voices), purple (special singing voices), red (strings), blue (drums). This grouping is in line with the findings of *Ward et al.* (2006a) that higher pitches are experienced as brighter colors.

When S is focusing on a particular portions of sounds (e.g. piano part in a song), the perception will "zoom" into the corresponding part of color field (e.g. the red color streams). When not focusing, the overall picture is perceived.

There are special patterns and structures in the colors, will be described in following sub-sections.

Musical instruments

The upper band and lower band of S's color field are evoked by different kinds of musical instruments.

In the upper band: Light blue is associated with cymbals (thin metal plates in a drum set). Yellow is associated with wind instruments with a clear sound, e.g. flutes. Sometimes there is a dotty pattern or wavy pattern. Orange is associated with wind instruments with an obvious airflow quality, e.g. saxophones, bagpipes.

[2] The two sounds are similar, but here we cannot make conclusion that her two sub-types of synesthesia are correlated, with only a few data.

In the lower band: Red is associated with string instruments, including guitar, violin, piano, and also electronic keyboard. Often it comes with a flat or volume feeling. For modern synthesized music (e.g. electronic keyboard) the feeling is flat, but for real instruments (e.g. violin), it is like gaining a three-dimensional volume with light and dark shades, and is described as "Youtube red" because it resembles the logo of that website. Blue is associated with drums. Sometimes the blue is "polluted" by black color if the music is very noisy, like rock band sound.

We let S listen to unfamiliar instruments that she seldom or never heard of, like Chinese flute (Dizi) and Chinese strings (Guzheng). They still have yellow color (as flute) and red color (as strings), but are not pure. For Dizi, there are orange dots under the yellow band, and for Guzheng, there are other colors "hidden behind" the red waves.

In certain occasion, color patterns could be very complex. For example when S was once emotionally engaged in a musical theater performance, she recalled the synesthetic experience as "a red line with gradient red bubbles attached, yellow spiral, in blue background" (Figure 15, bottom-right pattern).

Human voices

The middle band of S's color field is associated with human voices.

In usual case, human speaking voices are green, and singing voices are yellowish green. They both have a texture of tree leaves (as a metaphor).

A much unexpected aspect is the change in color when the speaker is telling a lie. S describes that when a person is lying, his voice is "losing its color" and become grayish green.

Orange, purple and red (all adjacent to green color band) could also occur in human singing voices, but only for some special singers. Pop singer Cher is purple with orange dots, and reversely, Bonnie Tyler is orange with purple dots. S noticed a similarity between the two female singers – both are powerful and have a nasal quality. The beautiful voice of Tamashiro Chiharu (in Japanese duo Kiroro) has color of normal green with orange dots. Many black singers, having voice quality different from Caucasian and Asian people, have a red singing voice.

Other sounds

Compare to the vivid colors above, other environmental sounds (e.g. furniture moving) have more natural colors such as brown. In one occasion, sound made from plastic wrapping of a product had a complicated experience – 4 colors producing a pattern (see Figure 15, top-right pattern).

4.3.3. Analysis of S's Synesthesia

Sensitivity to sound quality

Even not being a professional musician, she shows a high sensitivity to the quality of sounds, manifested as various colors and patterns.

The most interesting indication comes from her ability to distinguish between a normal speaking voice and a lying voice, which are perceived as different saturations of green color. This could be related to the change in human voice quality under stress, such as instability or tone change. In fact, Voice Stress Analysis, a new kind of lie detection technology, intends to use "micro tremors" (tiny shakes; Lippold, 1971) in a voice to detect if the speaker is lying.

S's synesthesia could also capture certain subtle qualities in human singing voices. Normally, a singing voice is just green, but for special singers, the voice could also have orange, purple or red. An explanation could be similarity to musical instruments. Nasal quality in some voices may evoke orange (as wind instruments), while harmonic quality in black singers may evoke red (as string instruments).

Inside a song, S could easily identify which instruments are playing, by just telling which colors are present. For example, "piano is there because I see red." Also, she can distinguish between real instruments (e.g. a violin in real concert) and synthesized music (e.g. violin sound mimicked by an electronic keyboard) – the former gives a three-dimensional color stream with light and dark shades, while the later gives a flattened stream.

All these examples demonstrated a high sensibility to audio stimuli without corresponding musical training. This is in line with anecdotal reports that synesthesia might be more common among individuals with absolute

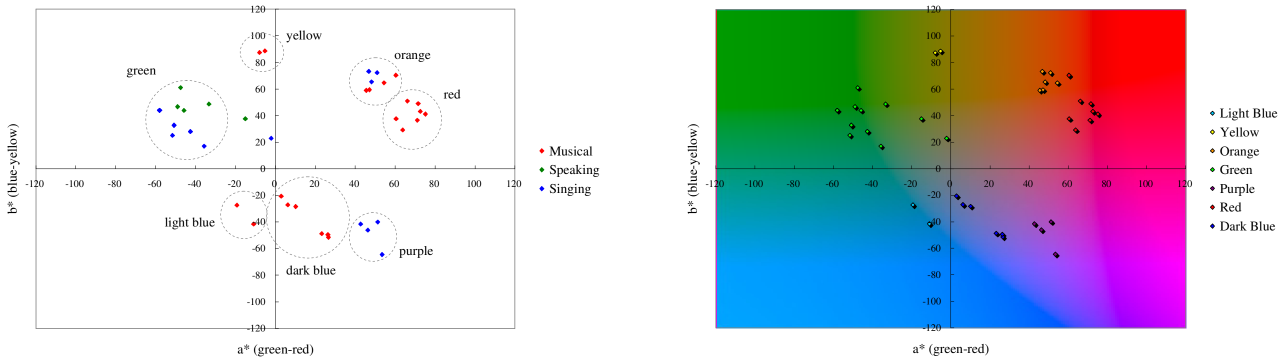


Figure 17: Distribution of S's colors in the CIE-Lab a x b* space, with data series in inducer type (left) and color type (right).*

pitch, in that colors allow them to uniquely identify musical tones. (Ramachandran & Hubbard, 2001b)

Distribution over color space

We expect that S's synesthetic colors are localized in color space, since her colors are already organized into different bands in visual field.

This is confirmed by the graphs showing S's color distribution, as in Figure 17. The graphs are plotted with axes a* (determining blue-yellow hue) against b* (determining green-red hue) in CIE-L*a*b* color model. All colors in raw data table except "Other sounds" are used.

5. General Discussions

As presented in previous result and analysis section, synesthetic experiences of the three participants, though not a statistically significant population, hinted several interesting traits. Some of the traits are quite elaborated in the analysis, but some are only a loose grasp, need future studies and experiment to confirm. They will be discussed here as a conclusion to this report.

5.1. "Aha, I never thought of it!"

When the analysis results in this report, especially the grouping of colors, are shown to the participants themselves[3], they often feel surprised. Exclamations are like "aha, I never thought of it!" or "that was an epiphany!" At the same time, they agreed most of the analyses are reasonable to them.

This unexpectedness demonstrates that synesthesia is really an automatic and natural part of their perception, like normal vision and audition. In fact, all of the participants said that their synesthesia rarely goes to the conscious level, unless somebody really ask about it.

An analogy is that, when looking at the sea and the sky that both are blue, we seldom ask "why they have similar colors?" Similarly, synesthetes seldom ask "why letters A and E have similar colors?"

5.2. Lighting and pattern processing

In response to the special properties observed in synesthesia of the participants, we have a hypothesis that there should be corresponding processing areas in the human visual cortex.

Lighting properties and "lighting processing area"

As mentioned in the results part of B, his synesthetic experiences have many additional properties other then colors, such as transparency, metallicity, and a quality called "contrast". Indeed, these qualities could be explained as *analogies to everyday lighting effects*. Transparency is having a light source from behind, metallic color is light reflected from a light source above, and glowing color is the light source itself. For "contrast", it is more complicated, but could be related to transparency.

Consequently, besides the color processing areas in the human visual cortex, we suspect that there would be a *lighting processing area* in the visual cortex.

3 After all data are collected, for confirmation and comments.

Ramachandran and Hubbard (2001b) proposed a "cross-wiring hypothesis" that grapheme–color synesthesia is caused by cross-wiring between two adjacent brain areas, such as between visual grapheme area and color area (V4) in the fusiform gyrus, or between angular gyrus (deal with abstract number representation) and a higher color area in the superior temporal gyrus. Their theory is in response to the fact that colors are involved in synesthesia, but what if lighting properties are also involved? Could it be explained by cross-wiring with an undiscovered brain area?

If this lighting processing area is possible to exist, we further suspect that it is located near the angular gyrus. In B's experience, all the lighting effects – transparency, metallicity and "contrast" – mostly associated with abstract numerical and mathematical concepts, corresponding to the abstract number functioning of the angular gyrus. Cross-wiring should occur to an adjacent area of it.

Furthermore, in a short essay by Ramachandran and Rogers-Ramachandran in the magazine *Scientific America Mind*, they suggested that our transparency perception should have evolved to deal with shadows and to distinguish them from real objects (Ramachandran and Rogers-Ramachandran, 2008). If our ability to process transparency (and other lighting conditions) is an essential function throughout human evolution, it should justify having a centralized "processor" inside our brain.

Colorful patterns and "pattern processing area"

Much like lighting properties, the colorful patterns in K's experience are also intriguing. There are even complex and dynamic patterns in S's sound—color synesthesia, which may due to the fact that audio stimuli are dynamic and temporal, while visual stimuli are static.

Thus, in analogy to the lighting processing area, we also hypothesize a *pattern processing area* in the human visual system. Again, using the cross-wiring hypothesis of Ramachandran and Hubbard (2001b), we could say that the synesthetic patterns experienced by K and S are caused by cross-wiring with an unknown brain area.

In K's case, if this pattern processing area exists, it could be located at the fusiform gyrus. As a lower synesthete, K's colors and patterns are mostly related to the geometrical qualities of the graphemes. Thus, the grapheme area and color area V4 in the fusiform gyrus (lower synesthesia channel), as well as the hypothetical pattern processing area, should be adjacent to each other for cross-wiring.

This theory is consistent with the work of Gonzalez *et al.* (2006), where their electrode experiments further support an existing idea that the fusiform gyrus is related to color and pattern perception.

5.3. Origin of synesthetic colors

Several noticeable cases described in this report could give some hints on how the synesthetic colors are originated.

In the analysis of K's case, we found a striking relation between colors and stroke orders of graphemes. This strongly suggests that the grapheme—color associations were created at the time when handwriting was learnt in early education.

In several occasions B expressed a strong influence of learning processes on his colors. Firstly, "cosine" has two different color versions according to his level of understanding of the concept. Secondly, Greek small letter eta (η) obtained its color from Roman letter N, but with an exceptionally dark tint. B explained that it came from another Greek small letter xi (color black) when he learnt the two letters at the same time.

From these cases, we cannot conclude *where* exactly the synesthetic colors came from, but can say something on *how* the synesthetic colors are obtained – i.e. during the *learning process* of the inducers.

When a new concept or procedure is being learnt, a new series of neuron connections will be set up inside the brain's neural network. For non-synesthetes, these new connections are just linking the relevant parts. However, inside the brain of synesthetes, there is something more. If the cross-wiring hypothesis of Ramachandran and Hubbard (2001b; mentioned in section 5.2) is correct, there will be extra neurological channels inside the network.

For example, when a new letter "A" is being learnt in class, the corresponding brain parts (for visual image, audio voice, mouth articulation, and hand movement) will have lots of neurons stretching their little axons to each others. However, inside a grapheme—color synesthete, the axons will also reach the part of color vision though an extra channel. If the synesthete related letter “A” to color “brown” during the learning process (maybe appear in textbook, maybe color of teacher’s shirt, maybe thinking of her brownish dog named “Ace”), then an “A—brown” association is established.

Once a person learnt about “A”, its associated shape, sound and finger movements will not be changed throughout the lifetime. The same occurs in synesthesia – its association to “brown” will not be erased or changed by any means. This could explain why synesthetic experiences are consistent over long time: they are just the same as other learning connections.

Furthermore, if there are physiological or psychological rule governing the extra neuron connections, certain universal trends may occur, as found in various statistical studies. E.g. higher pitches tend to have brighter colors (Ward *et al.*, 2006a), and smaller numbers tend to have brighter colors (Cohen Kadosh *et al.*, 2007).

This theory (we call it “little axons theory” for some reason) is in line with some recent studies. Direct evidence has been found that exposure to certain toys or learning tools in childhood (e.g. colored jigsaw puzzle; colored refrigerator magnets) actually link to synesthetic experiences in adulthood (Hancock, 2006; Witthoft & Winawer, 2006). In the statistical study of Rich *et al.* (2005), there is no significant evidence, but they still found 5 out of 150 synesthetes that have 77%-100% of consistency between synesthetic colors and colored alphabet/number books.

Finally, we could explain why there are so little evidences of linkage between synesthetic experiences and particular objects – the associations could be just *random*. A color (or any concurrent) could have come from an object, an imagination, the environment, or anything happened at the moment. Also, it is nearly impossible for an insignificant event in early childhood to be recalled after grown-up. So nobody, including synesthetes themselves, could have information on *where* the associations came from.

5.4. Synesthesia and qualia

We often say that synesthetes “see” the colors, but it is most likely that the synesthetic experiences are very different from normal color perception. Colors, patterns, lighting effects, all are out there in their brain, but they are often difficult to express in words.

During interviews with B, when something is not simply a color, he usually gave expression like “it’s hopeless to tell what’s happening”. He tried to employ metaphors or match it with everyday experiences, but is not always satisfied. Sometimes, several different valid explanations are given for one experience.

S also expressed this difficulty. When she hears the same piece of sound or music, there is always the same experience of colors and patterns, but she “cannot exactly translate them into simple colors”, and could only choose a “representative color” for it. Metaphors are also employed to explain patterns, for example human voices are like “leaves on a tree”. When we showed to S our depiction of her patterns (Figure 15, bottom), she gave a comment: “the patterns (like dots) are more difficult to portray and are here just representational”.

These difficulties may come from a lack of lexicon in our languages, as the synesthetic experiences are not common to the whole population. However, it may be more plausible to explain by *a lack of common qualia*. A “qualia” is a quality that you have to experience by yourself, and cannot be transferred to others directly (unless telepathy is possible). For example the color “red” is a qualia. You can tell someone that a rose is red, by saying the word “red” to evoke this common experience. But if the receiver is a blind person since birth, you cannot tell him what is red in anyway. Even if you say “red is the color of fire, red is like love, red is light with wavelength 625–740 nm”, they are just metaphors or scientific facts, the blind person still gets nothing.

The situation is the same here. When a synesthete tells you the association of a voice is “like the green tree out there with a few orange leaves”, it is only a metaphor, not the synesthetic experience itself. You can know what exactly happens in her synesthesia only if it is a common qualia between you and her, which is quite impossible even if you are also a synesthete.

Further discussion of qualia and synesthesia could be found in Ramachandran and Hubbard (2001b).

5.5. Sensitivity of color matching and “absolute color”

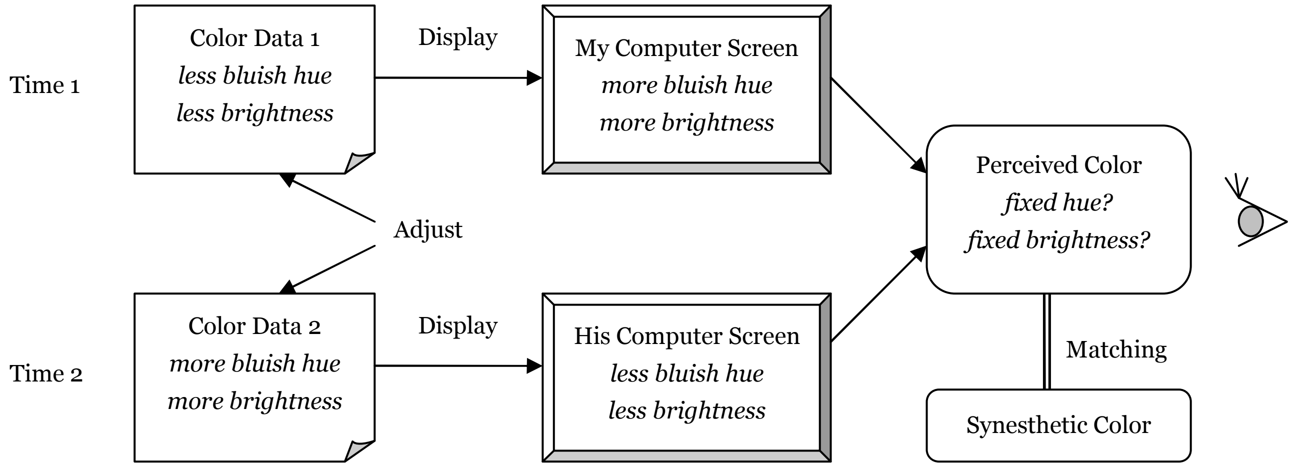


Figure 18: The principle of counter adjustment in matching synesthetic colors. If the synesthete can adjust color data so that the perceived color is the same in different environments, we could say he has "absolute color".

In one of Galton's pioneering study (1883), he observed that those with visual synesthesia are "invariably most minute in their description of the precise tint and hue of the color. They are never satisfied, for instance, with saying 'blue', but take a great deal of trouble to express or match the particular blue they mean."

This is exactly the same situation as participant B. While matching a color, he would give verbal adjustments like "a bit lighter/darker", or fine-tuning in ColorPicker program by ±5 in RGB values.

This kind of fine adjustment should give very accurate choices in the colors. However, in fact, he chose different shades of colors in two different lighting conditions and equipments, as shown in Figure 9 of section 4.1.3. One interesting phenomenon is that the colors are adjusted *opposite* to the environment conditions. In time 1, the computer screen used was brighter[4] and more bluish, and the colors he chose were oppositely dimmer and less bluish. The reverse occurred in time 2, dimmer and less bluish the screen, brighter and more bluish the color choices.

This strongly suggests that, although the *color data* (i.e. chosen color values) differ in two situations, the *perceived colors* displayed on the screens are very likely the same color (same hue and same brightness). The principle is illustrated in Figure 18. Color data are adjusted by the synesthete to compensate the difference in screen settings, in order to produce the same perceived color that accurately matches with the synesthetic color.

We use a new term *absolute color* to describe this ability of identifying a color with fixed hue and brightness (and hence fixed wavelength and luminance of light) unaffected by the environment. This is analogous to absolute pitch, the ability to identify the exact frequency of a musical note.

Absolute color in the synesthete is significant, because it bypasses our faculties of color constancy and lightness constancy. A color with certain hue will be perceived as another hue when affected by surrounding color tone (color constancy), and a color will seemingly brighter under a shadow than outside the shadow (lightness constancy). These are automatic processes in the brain to adopt the continuously changing world.

In the future, psychological experiments could be conducted to confirm this hypothesis, for example, by testing if the synesthete will choose the same color in different color tone surroundings and shadows (refer to the experiments by Witthoft and Winawer (2006) for synesthesia and lightness constancy). Numerical evidence of invariance in perceived color (e.g. detecting the frequency and luminance displayed on screen) could also help, but it will be more complicated in experimental settings.

[4] Here we have an assumption that, under bright sunlight (as in time 1), we will set our computer screen brighter to counter-react with the environment; similar for dim sunlight (as in time 2), we will set the screen dimmer to ease our eyes.

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Appendix A – Questions Asked in Survey

Here we list the general questions given to the participants during the case study interviews.

General information

- Which of your sense is associated with which another sense? (e.g. letters evoke colors, sounds evoke colors… or anything else)
- When and how did you learnt about your synesthesia?
- Do you feel embarrassed when talking about it to other people (e.g. friends, family)? How do they think about it?
- Do your know any of your family or friends who also has synesthesia?
- Does synesthesia annoy you in daily life, or help you in some way such as in studying and career?

List of color associations

- Is color association applied to all stimuli in the type? (e.g. if letters evoke colors, is that each letter from A-Z evokes a color?)
- Can you give examples or listings of the color associations? (e.g. number 1 is black…)
- Do you prefer choosing the colors using color palette booklets (which one), or fine-tuning in a computer program?
- Do you feel any difference when choosing colors in different times, equipments or environments?
- If I show you the color blocks I made according to your color choices (e.g. Figure 1), do you recognize that they are "your colors"? Any deviations?
- Do you notice any similarities or trends in your colorings?
- If I tell you my analysis of your colors, do you think it makes sense?

Quality of color associations

- Are the colors projected on the letters, projected on a screen, or just inside your brain or "mind's eye"?
- If a letter is printed in green but you color to it is red, can u see both green and red at the same time?
- Do you see the colors when actually seeing the word, or merely think about it?
- If you only imagine the stimulus (e.g. word, sound), is the color more vivid?
- Is there any difference in words/concepts using different languages (e.g. English, Swedish, Skånska)? How about other languages?
- Is there any difference in capital/small letters and different font types?
- Is there any difference in forms of numbers? (e.g. Arabic number, Roman number, dice dots)

Appendix B – Conversion between Color Spaces

The color models used in this report (RGB, HSV, CMYK, CIE-L*a*b*) are briefly described in section 3.3.1. Here we list out the conversation rules between color spaces in computer programming pseudo-code format. The codes are obtained on "Color conversion math and formulas" section in *EasyRGB* website by Irotek (2008), and are used in computer program ColorPicker as well as data analysis in Microsoft Excel.

6.1. CMYK → RGB

```
//CMYK values from 0 to 1
//RGB results from 0 to 255
var_C = ( C * ( 1 - K ) + K )
var_M = ( M * ( 1 - K ) + K )
var_Y = ( Y * ( 1 - K ) + K )
R = ( 1 - var_C ) * 255
G = ( 1 - var_M ) * 255
B = ( 1 - var_Y ) * 255
```

6.2. RGB → HSV

```
//RGB from 0 to 255
//HSV results from 0 to 1
var_R = ( R / 255 )
var_G = ( G / 255 )
var_B = ( B / 255 )

var_Min = min( var_R, var_G, var_B )
var_Max = max( var_R, var_G, var_B )
del_Max = var_Max - var_Min

V = var_Max
if ( del_Max == 0 ) {
   //This is a gray, no chroma...
   H = 0
   S = 0
} else {
   //Chromatic data...
   S = del_Max / var_Max
   del_R = ( ( ( var_Max - var_R ) / 6 )
            + ( del_Max / 2 ) ) / del_Max
   del_G = ( ( ( var_Max - var_G ) / 6 )
            + ( del_Max / 2 ) ) / del_Max
   del_B = ( ( ( var_Max - var_B ) / 6 )
            + ( del_Max / 2 ) ) / del_Max

   if ( var_R == var_Max )
      H = del_B - del_G
   else if ( var_G == var_Max )
      H = ( 1 / 3 ) + del_R - del_B
   else if ( var_B == var_Max )
      H = ( 2 / 3 ) + del_G - del_R

   if ( H < 0 ) H += 1
   if ( H > 1 ) H -= 1
}
```

6.3. RGB → CIE-XYZ

```
//RGB from 0 to 255
//XYZ results from 0 to 100
var_R = ( R / 255 )
var_G = ( G / 255 )
var_B = ( B / 255 )

if ( var_R > 0.04045 )
   var_R = ( ( var_R + 0.055 ) / 1.055 ) ^ 2.4
else
   var_R = var_R / 12.92
if ( var_G > 0.04045 )
   var_G = ( ( var_G + 0.055 ) / 1.055 ) ^ 2.4
else
   var_G = var_G / 12.92
if ( var_B > 0.04045 )
   var_B = ( ( var_B + 0.055 ) / 1.055 ) ^ 2.4
else
   var_B = var_B / 12.92

var_R = var_R * 100
var_G = var_G * 100
var_B = var_B * 100

//Observer. = 2°, Illuminant = D65
X = var_R * 0.4124 + var_G * 0.3576 + var_B * 0.1805
Y = var_R * 0.2126 + var_G * 0.7152 + var_B * 0.0722
Z = var_R * 0.0193 + var_G * 0.1192 + var_B * 0.9505
```

6.4. CIE-XYZ → CIE-L*a*b*

```
//XYZ from 0 to 100
//CIE-L* result from 0 to 100
//CIE-a* result from -83.85 to 98.25
//CIE-a* result from -107.86 to 94.48

//ref_X =  95.047   Observer= 2°, Illuminant= D65
//ref_Y = 100.000
//ref_Z = 108.883
var_X = X / ref_X
var_Y = Y / ref_Y
var_Z = Z / ref_Z

if ( var_X > 0.008856 )
   var_X = var_X ^ ( 1/3 )
else
   var_X = ( 7.787 * var_X ) + ( 16 / 116 )
if ( var_Y > 0.008856 )
   var_Y = var_Y ^ ( 1/3 )
else
   var_Y = ( 7.787 * var_Y ) + ( 16 / 116 )
if ( var_Z > 0.008856 )
   var_Z = var_Z ^ ( 1/3 )
else
   var_Z = ( 7.787 * var_Z ) + ( 16 / 116 )

CIE-L* = ( 116 * var_Y ) - 16
CIE-a* = 500 * ( var_X - var_Y )
CIE-b* = 200 * ( var_Y - var_Z )
```