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漢字色彩聯覺的語言因素探討

What Linguistic Factors Determine the Similarity in Synesthetic Color in Chinese?

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於是，終於走到了這一步。

六年前，在「跨感官消息處理」的課堂上，彷彿受到「聯覺」這個主題的感召，一腳跨入了這個世界。過程中，有過對自己的懷疑和無助感，也曾感受到追求和分享知識的喜悅。迂迴前進在這研究路上好些年，總算能踏出完成碩士論文的最後一步。而這一步，心中有許多感謝。

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摘要

字色聯覺指的是在觀看無色的文字或數字時，會產生額外的色彩知覺。多數對於字色聯覺的研究多著重在拼音文字的語言（例如：英文），並發現特定的語言因素會系統性地影響感受到的聯覺顏色（例如：B 連結到藍色），但對於表義文字系統（例如：中文）是否也存在類似的關聯性，仍有待進一步的探討。本研究選用四組無色漢字來釐清四個語言因素（字形、字音、字義、及表義單位）和聯覺顏色之間的關聯。我們透過一致性測驗，篩選出具有漢字字色聯覺者的參與者進行實驗。分析這些聯覺者字與字之間的聯覺顏色相似性，結果發現字義關聯性高以及重複部件（部首或聲旁）這兩項因素，顯著地和聯覺者所感知的色彩相似性有關。同音字的色彩相似性僅在聲旁重複時顯著較高，且重複聲旁也僅在同音時色彩會顯著相似，顯示部件的表音功能，也在聯覺顏色的形成扮演重要的角色。連綿詞無論是否有語音相似性（重複聲母或韻母），皆傾向引發相似的聯覺顏色。先前研究顯示英文字色聯覺者會將單字的顏色與首字或首母音連結，而漢字的聯覺則沒有單一因素可以決定整字的顏色，顯示中文字色聯覺的現象，包含了不同層次的心理語言處理歷程。

關鍵字：色彩聯覺、漢字處理歷程、語意關聯性、部首、聲旁、同音字、連綿詞

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What Linguistic Factors Determine the Similarity in Synesthetic Color in Chinese?

Huan-Wei Lin

Abstract

Grapheme-color synesthetes perceive unusual color perception when seeing colorless letters or digits. Previous studies on grapheme-color synesthesia used mostly alphabetic writing system, and found specific rule-based linguistic factors related to the perceived synesthetic color. However, whether similar mechanisms exist in logographic languages such as Chinese remains mostly unknown. We manipulated four linguistic factors (orthographic, phonetic, semantic, and morphemic) of Chinese characters and examined how these factors influenced the color-mapping of Taiwanese grapheme-color synesthesia. Synesthetes with grapheme-color synesthesia of Chinese characters who passed the synesthesia consistency test performed a color-matching task using four sets of Chinese characters, which were used to clarify the role of different linguistic factors that could be related to the color mapping of the synesthetic color. We found that semantic relatedness and orthographic similarity (repeated semantic radicals and repeated phonetic radicals) played a significant role in synesthetic color similarity. Phonetic similarity was correlated with synesthetic color similarity only when two characters shared the same phonetic radical, and repetition of phonetic radical was also correlated with synesthetic color when the pronunciation was the same. This interaction effect suggested that the radical function of Chinese characters is involved in synesthetic color mapping. We also found that regardless of various similarity in their pronunciations, the character pairs from binding words that form a single morpheme had similar synesthetic color. While studies of English lexical synesthesia showed a rather clear correlation between the first

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letter/vowel and the synesthetic color of the word, we found in the current study that no single factor could exclusively determine synesthetic color mapping in Chinese. These findings indicate that the grapheme-color synesthesia of Chinese characters involves multiple levels of language processing.

Keywords: Synesthesia, Synesthetic color mapping, Chinese character processing, Radical function, Semantic relatedness, Pronunciation, Homophone, Binding words

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Contents

1. Introduction 1
1.1 Color Mapping of Synesthesia: First-order and Second-order Mapping 2
1.2 Chinese Writing System and Language Structure 3
1.3 Synesthesia Studies on Chinese Characters 5
1.4 Spatial Pattern Analysis of Synesthetic Color Distribution 7
1.5 Goals of This Study 8
2. Method 11
2.1 Participants 11
2.2 Apparatus 12
2.3 Materials and Design 13
2.4 Procedure 15
2.5 Data Analysis 16
3. Results 19
3.1 Distribution of Synesthetic Color in CIE L*a*b Color Space 19
3.2 Semantically Related Characters Without Repeated Radicals (Set1) 21
3.3 Transparent-transparent (Set 2) and Transparent-opaque (Set 3) Semantic Pairs with repeated semantic radicals 22
3.4 Homophone Pairs Without Repeated Radicals (Set 4) 23
3.5 Phonologically Related Characters with Repeated Phonetic Radicals (Set 5 and Set 6) 24
3.6 Binding Words (Set 7 and Set 8) 26

doi:10.6342/NTU201903697

3.7 Linear Mixed Effect Model Analysis 27

3.8 Correlation Analysis 30

4. Discussion 32

4.1 Semantic Relatedness 33

4.2 Pronunciation Similarity 34

4.3 Orthographic Similarity 36

4.4 Morpheme 37

4.5 Individual Difference 38

5. Conclusion 40

6. References 41

Appendix 1. Summary Table of Color Similarity Index (CSI) for Each Synesthete .47

Appendix 2. Character Material List 48

Appendix 3. Density Plot and L-function of Each Synesthete 53

doi:10.6342/NTU201903697

List of Figures

Figure 1. The color palette used for synesthetic color selection, adopted from Eagleman et al. (2007)..........13
Figure 2. An example of spatial distribution of synesthetic colors in the CIE L*a*b* (1976) uniform color space based on the data collected from synesthete YHC..........20
Figure 3. Results of color similarity for semantically related characters without repeated radicals..........21
Figure 4. Results of characters with the same semantic radicals but differing in semantic transparency..........23
Figure 5. Results of characters with the same pronunciation..........24
Figure 6. Results of characters with the same phonetic radicals but differing in their phonological relatedness..........25
Figure 7. Results of binding words formed by two characters with a single morpheme 27
Figure 8. Relation between slopes and scores of the subjective synesthetic experience for different linguistic factors..........31
Figure 9. Results of mean color similarity index of each character set..........32

doi:10.6342/NTU201903697

List of Tables

Table 1. Demographic and Synesthetic Characteristic of Participated Synesthetes 12

Table 2. Summary of group-level analysis of all the results 28

Table 3. Results of linear mixed effects models on different linguistic factors and color similarity index (CSI) 30

doi:10.6342/NTU201903697

1. Introduction

Synesthesia is an uncommon perceptual phenomenon that can be found in around 4.4% of the population (Simner, Mulvenna, et al., 2006). People with synesthesia usually experience a stimulus (i.e., a trigger) in one sensory modality triggering an additional perceptual experience (i.e., concurrent) within the same or in a different sensory modality (e.g., hearing a sound of high G or seeing a black letter A triggers the sense of color red). For the identified forms of synesthesia, around 80~90% of them is triggered by language; for example, grapheme-color synesthesia is the most common type of synesthesia in which synesthetes associate specific colors with particular numbers or letters. By investigating the relationship between the trigger and its concurrent, more and more studies have unveiled the complexity of the underlying psycholinguistic system that underlies the synesthetic experience (Simner, 2013). Another aim of this field is to use linguistic synesthesia to infer information about normal language processing; for example, to compare the development of linguistic synesthesia and the acquisition of language (Rich, Bradshaw, & Mattingley, 2005). By applying psycholinguistic approaches to the study of linguistic synesthesia, researchers can relate results obtained from studies of synesthesia to general theories of language processing (Ramachandran & Hubbard, 2001; Simner, 2007).

Although the synesthetic experiences of linkage between triggers and the particular synesthetic perception are idiosyncratic, some rules have been identified in previous studies of grapheme-color synesthesia in alphabetic languages. For example, many grapheme-color synesthetes systematically perceive the whole word's color based on the first letter of the word (e.g., the letter C is yellow, so the word "chair" is yellow; Ward, Simner, & Auyeung, 2005), or first/stressed vowel (e.g., the letter A is red, so the word "happy" is red; Simner, Glover, & Mowat, 2006). In some words with high imagery

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values, the synesthetic color could be the inherent real-world color (e.g., the word "water" is blue). These are regularities in such first-order color mapping, as we will discuss in the next paragraph, that provide information about from where a specific synesthetic color comes.

1.1 Color Mapping of Synesthesia: First-order and Second-order Mapping

Watson, Akins, and Enns (2012) proposed two levels of color mapping in grapheme-color synesthesia: first-order and second-order color mapping. Studies of the first-order color mapping are more related to how the association between the trigger and the concurrent is made. For example, English speakers often relate the synesthetic color of letters according to related color terms (e.g., B is blue, G is green, etc.), frequently used words (e.g., A is red because Apple is red), or even colors of letter-shaped fridge magnets used in their childhood. The relation can also be extended to word level, as the first-letter or first/stressed vowel rule we mentioned above.

On the other hand, studies of second-order relationship, meaning the relation between relations, provide information about why some letters or words trigger similar synesthetic hue or luminance. Note that our color perception has not only the dimension of hue (people often use “color” to refer to the dimension of hue, and we use it interchangeable here as well), but also saturation (how closely the color is to white, the closer the less saturated) and luminance (defined as *V’* in CIE 1931) or brightness (defined as *value* in the 1921 Munsell color system). Watson et al. (2012) analyzed 54 synesthetes and concluded that on average, shape similarity (e.g., letter E and F are more similar than E and Q) and ordinal distance of letters (e.g., the distance of letters A and E is nearer than that of A and G) are correlated with hue similarity, while similarity of letter frequency (e.g., letter A is more frequently used than X) is correlated with luminance similarity.

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That is, the nearer the ordinal distance or the more similar the shape between letters, the more similar their hues are, and the more frequently used of a letter, the higher the luminance. Kang, Kim, Shin, and Kim (2017) also found that Korean synesthetes showed a similarity of synesthetic color based on phonetic characteristics, regardless of whether it is within the same language (e.g. bilabial sound "ㅂ/p/" and "ㅍ/pʰ/") or between different languages such as English (letter "M") and Japanese (み[mi]). These studies suggest that synesthetic coloring is not random, but rather, is systematically influenced by psycholinguistic factors that involved in the process of normal language comprehension.

Although the synesthetic coloring of English and other languages with alphabetic/phonetic spelling languages have been relatively more widely studied, it remains largely unknown about the synesthetic coloring of logographic language such as Chinese. To our knowledge, only two studies (Hung, Simner, Shillcock, & Eagleman, 2014; Simner, Hung, & Shillcock, 2011) systematically investigated synesthesia in Chinese. Below we briefly review the two studies, and compare them to other research of synesthetic coloring in Japanese (Asano & Yokosawa, 2011, 2012), a writing system consists of both phonetic and logographic characters.

1.2 Chinese Writing System and Language Structure

The basic unit of Chinese writing system is the square-like character, and each of which has a similar size and corresponds to one syllable and one morpheme (except for binding words, which require two characters to form one morpheme). Although some of Chinese characters have relatively simple structures and fewer stroke numbers, which may be originated from ancient pictogram (e.g., 山, 'mountain'), most of characters are with a complex internal structure: about 70~80% of traditional Chinese characters are

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classified as phonograms that consist of one semantic radical and one phonetic radical (Liu, Su, & Chen, 2001). For example, the phonogram 材 ([tsai2], "timber") contains two radicals: the semantic radical 木 ([mu4], "tree") on the left and the phonetic radical 才 ([tsai2],"ability") on the right. Like in this example, the semantic radicals of Chinese phonogram usually appear on the left while phonetic radical on the right. However, other compositions are also possible. For example, 鴉 ([ia1], "crow") consists of the semantic radical 鳥 ([niau3], "bird") on the right and the phonetic radical 牙 ([ia2], 'tooth') on the left.

Although Chinese radicals in characters can function semantically or phonetically as to cue the meaning or pronunciation of the character, it is not always the case. Chinese characters are usually sorted by semantic radicals in a dictionary, and most semantic radicals, as defined, are semantically related to the characters containing them. For example, characters containing the radical 木 ('tree'), such as 枝 ("branch"), 柳 ("willow"), or 椰 ("coconut") have categorical meanings related to 'tree', and the relationship between the semantic radical and the character containing it is considered as transparent. However, some characters have meanings that are vaguely related to the radicals, like 極 ("extreme") or 概 ("roughly"), and the relationship is opaque between the semantic radical and the character within which the radical is embedded. Similarly, phonetic radicals may provide clues of pronunciation such as 材 ([tsai2]) and 財 ([tsai2]) which contain the phonetic radical 才 ([tsai2]), but the pronunciation of character 閉 ([bi4]) is different from the pronunciation of its phonetic radical.

Another characteristic of Chinese is the frequent occurrence of homophones. Nearly 1200 different pronunciations are used in Mandarin Chinese, while 99.7% frequently used

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characters consists of about 4000 characters. For example, there are 30 distinct characters all pronounced [yi1] in Mandarin, and the average homophones of a character is 11 (Perfetti & Tan, 1998). Regardless of the existence of many homophones, spoken Chinese is still understood without difficulty with the context.

One more characteristic worth mentioning is that although there are around 4000 frequently used mono-syllabic characters, most of the words are compound (or, disyllabic) words, composed of two or more constituent characters (i.e., morphemes). X. Zhou and Marslen-Wilson (1999) estimated the proportion of compound words in Chinese as about 74% by type (i.e., repeated words were counted once) and 34% by token (i.e., repeated words were counted everytime). As in the example, the word 南瓜 ("pumpkin") is composed of two characters/morphemes 南 ([nan2], "south") and 瓜 ([gua1], "melon"). In Chinese, some monomorphemic compounds consist of two characters that always appear together to make a word, like 葡萄 ([pu2 tao2], "grape"). These monomorphemic compounds are called “binding word” because none of each character of the binding word can stand alone to make a complete meaning (e.g., 葡 alone does not mean anything, nor does it mean half of a grape).

1.3 Synesthesia Studies on Chinese Characters

As mentioned, limited studies so far have focused on synesthesia in non-alphabetic language such as Chinese. Nevertheless, the population of Chinese language users consists of a large proportion of the entire population and the ignorance of it means ignoring a large proportion of the world population that use Chinese. Indeed, advanced understanding of the grapheme-color synesthesia in general and Chinese in particular

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provides a window into which both the underlying mechanisms of grapheme-color synesthesia and language processes can be better revealed.

Simner et al. (2011) showed that the synesthetic coloring of Chinese characters was influenced by the first phoneme of the pronunciation in some synesthetes, which seems in line with previous studies of synesthetic coloring in alphabetic languages. However, this result was mainly obtained from the synesthetes who learned Chinese as a second language or for those Chinese people who moved to western countries at an early age. For the native speakers of Chinese, however, such a result pattern was absent.

Hung et al. (2014) then presented a more systematic analysis on how radical function and position influence the synesthetic color, by recruiting Chinese-speaking synesthetes via the online synesthesia research website The Synesthesia Battery (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007). The participants were asked to match the synesthetic color for characters consisting of two radicals (e.g. 櫻([ying1], "cherry")), and their constituent radicals (e.g. 木([mu4], "tree") and 嬰([ying1], "infant")), respectively. They concluded that characters consisted of two radicals were darker and more saturated than their constituent radicals. Also, radical position and function were both influential: left radicals generally influenced the perceived hue while right radicals influenced the perceived luminance; semantic radicals also influenced the perceived saturation when located on the left. On the other hand, in the study of Asano and Yokosawa (2012), synesthetic color mapping in Japanese logographic Kanji characters depended on semantic meaning and phonological information, and little, if any, influence was found from the radicals.

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1.4 Spatial Pattern Analysis of Synesthetic Color Distribution

Compared to previous studies of grapheme-color synesthesia that often collected a relatively small amount of synesthetic color association per synesthetes (i.e., 26 synesthetic colors for the English alphabet), the nature of Chinese language that thousands of characters are frequently used allows the possibility of collecting a large amount of synesthetic color association. Hamada, Yamamoto, and Saiki (2016) collected hundreds of synesthetic color association of Japanese Kanji character, hiragana, and katakana per synesthete, and they analyzed how these synesthetic colors were distributed in the CIE L*a*b* uniformed color space. The spatial point pattern found in their study were not randomly distributed in the color space but showed a pattern of clustering, which means that some characters tend to have similar synesthetic color to each other. They conjectured that a first-order relationship determined some of the core colors of clustering in the formation of synesthetic color association, and then other synesthetic colors of late acquired graphemes or characters were determined according to the second-order relationship, such as those based on shape or phonological similarity. Since in the second process, the synesthetic color of a new learnt character was similar to the core color of the similar character, the synesthetic color distance between the two characters may be proportional to the distance of similarity between two characters, leading to a clustering distribution. In the present study, the spatial pattern analysis is suitable since a large amount of synesthetic color association would also be collected. We also assumed that a similar pattern would be found, although the critical linguistic factors are still unknown for Chinese characters used by Taiwanese synesthetes.

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1.5 Goals of This Study

In the present study, we aim to provide a systematic investigation of (1) the global feature of synesthetic color distribution in color space for Taiwanese synesthetes, and (2) how different linguistic factors, including phonology, semantic, orthography and morphemic, may affect the linkage between Chinese characters and synesthetic colors.

First, to investigate the global feature of synesthetic color distribution in color space, we adopted the spatial point pattern analysis developed by Hamada et al. (2016) and Baddeley (2008). Hamada et al. (2016) showed that synesthetic colors of kanji characters selected by Japanese synesthetes formed clustering patterns in the CIE L*a*b* uniform color space, which suggests the possibility of the second-order relationship playing an important role in the synesthetic color acquisition of newly learned characters. Since most of the Chinese characters are also learned in rather later in life, we assume that the color choices for these characters could also depend on orthographical, phonological, semantic or other linguistic information. If so, characters with similar linguistic factors could induce similar synesthetic color, leading to a clustering distribution in the color space. We assume that a similar pattern (clustering distribution) could be found in our study, which suggests the possibility of the second-order relationship playing an important role in the synesthetic color acquisition of newly learned characters (as we mentioned above), although the key factor associated with the synesthetic color of characters may be different from studies of Japanese Kanji (Asano & Yokosawa, 2012; Hamada et al., 2016). If we also find clustering patterns of induced color percepts by Chinese characters for our Taiwanese synesthetes, it would suggest that certain second-order relationships exist in our study as well. If so, our next step would be to investigate which linguistic factor contribute to character similarity more. In the second part, we investigated the role

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of different linguistic factors in synesthetic color similarity. More specific research questions are listed below:

Semantics. Although it has been widely accepted that sharing the same meaning could be associated with similar synesthetic color (Mroczko-Wąsowicz & Nikolić, 2014; Ramachandran & Hubbard, 2001), there is still no direct evidence in Chinese synesthesia studies. We hypothesize that Chinese characters would trigger more similar synesthetic color when they are semantically related, and also higher synesthetic color similarity for transparent than for opaque semantic relationship between the character and its semantic radical.

Phonology. It remains controversial whether logographic characters that share phonetic similarity would have similar synesthetic colors (e.g., Japanese and Chinese results; Asano & Yokosawa, 2012, Hung et al., 2014). We hypothesize that characters with similar pronunciations would have similar synesthetic colors only when the characters share the same phonetic radicals instead of same phonemes. This is similar to that in English speech-induced color synesthesia where the words that shared the initial grapheme fish and fell induce similar color, but not the word physics that share with them the initial phoneme but not the grapheme.

Orthography. Radicals play an important role in Chinese character recognition (Y.C. Chen & Yeh, 2015) and visual search (Yeh & Li, 2002). Characters sharing the same radicals usually look more similar in shape as well. We hypothesize that characters sharing the same radical (semantic or phonetic) would have more similar synesthetic colors because they are more similar in shape. Nonetheless, radicals not only have their

doi:10.6342/NTU201903697

own orthography, they also carry semantic or phonetic functions to cue the character containing them, although not valid all the time. We hypothesize that, in addition to adding shape similarity to the two characters that share same radicals, semantic radical may be more influential than phonetic radical because the former is more informative in reading and also because the shape-meaning relationship is closer in logograph Chinese.

Morpheme. Binding words that have two characters with only one morpheme, as introduced above, are unique in Chinese. We hypothesize that the two characters in binding words would have similar colors since they always appear together, and carry the same meaning. Along this line of reasoning, pronunciation similarity of the two characters in the binding words should not matter for the synesthetic color similarity.

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2. Method

2.1 Participants

Eleven grapheme-color synesthetes were recruited through online advertisement on Facebook group of NTU students and website of NTU psychology department (10 female, 18-25 years of age, mean age = 20.42). All participants spoke Mandarin Chinese as their first language and had learned English as their second language for about 10 years in their study years. All the participants reported seeing synesthetic colors when viewing Chinese Characters. All synesthetes showed high consistency (mean score = 0.71, all below 1.00) in the online synesthesia battery developed by Eagleman et al. (2007). All synesthetes conducted the Illustrated Synaesthesic Experience Questionnaires (ISEQ) and were classified as projectors or associators according to the scores from ISEQ (Skelton, Ludwig, & Mohr, 2009). One male and one female participants were classified as projectors because they reported seeing synesthetic colors outside their bodies and eight female participants were associators because they reported their experience of synesthetic color in their mind's eye. The ISEQ-score of participant YHC was classified as undetermined; she subjectively reported a more associator-like synesthetic experience, but sometimes she saw synesthetic color above the printed characters as well. See Table 1 for their demographic and synesthetic characteristics. All participants had normal or correct-to-normal visual acuity. They all gave inform consent before conducting the experiment. This study was approved by the review board of ethic committee at National Taiwan University (REC 201604HS009).

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Table 1

Demographic and Synesthetic Characteristic of Participated Synesthetes

Subject	Gender	Age	Synesthetic Type	ISEQ-score
YHC	female	22	Undetermined	0.17
CCD	female	21	Associator	2.17
YSL	female	18	Associator	3.5
YLK	female	19	Projector	-1.33
YPW	male	21	Projector	-3.5
CLC	female	19	Associator	1.33
HLC	female	20	Associator	3.83
MCH	female	19	Associator	5.33
YST	female	18	Associator	4.66
TCL	female	19	Associator	1.33
YTL	female	23	Associator	4

Note. ISEQ: Illustrated Synaesthesic Experience Questionnaires; values > 1.05 indicate the synesthete is an associator; values < -1.05 indicate the synesthete is a projector, and values between -1.05 and 1.05 is undetermined.

2.2 Apparatus

The stimuli were presented on a color 21-inched CRT monitor (1024 x 768 resolution, 60 Hz frame rate), controlled by a PC using Matlab 2014 (The MathWorks, Natick, MA). The whole experiment was conducted in the darkroom which the monitor provided the only light source. The viewing distance between the participant and the monitor was approximately 80 cm, and each character in the experiment was BiauKai word font with 80pt font size (2 degrees of visual angle).

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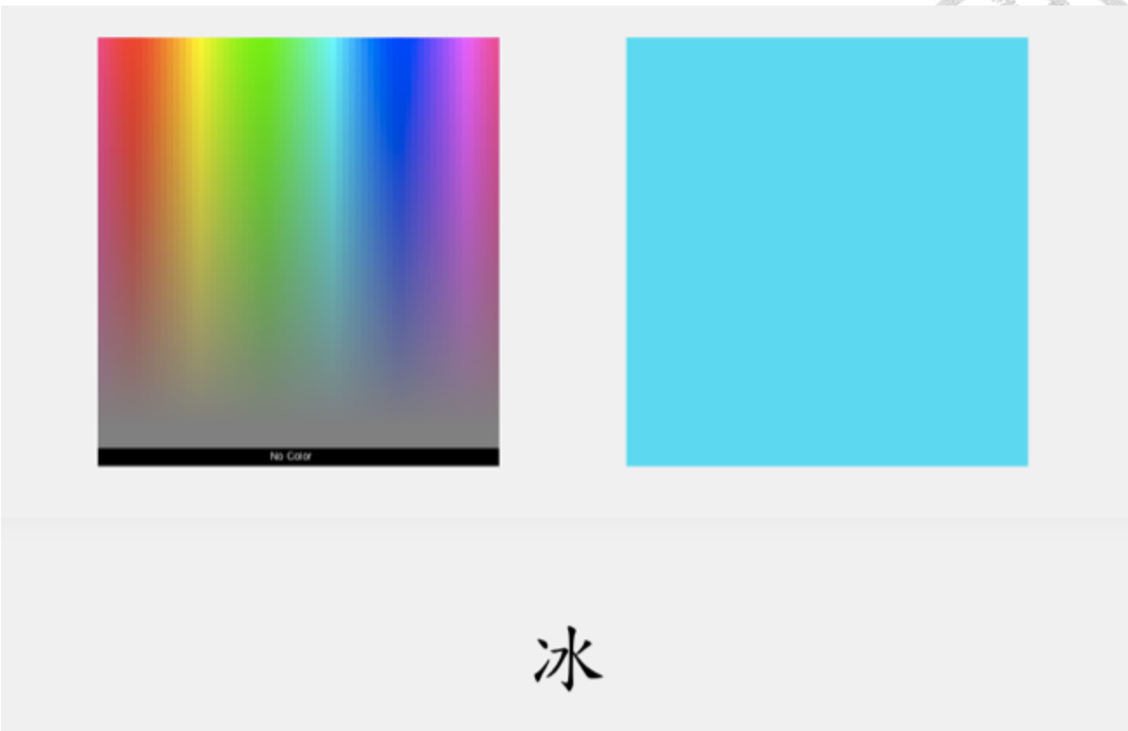

Figure 1. The color palette used for synesthetic color selection, adopted from Eagleman et al. (2007). The test character was presented at the bottom (the example here is a character 冰 from one of the homophone pair) and the synesthetic color was selected from the palette on the top left. On the top right is the preview of the selected color. A “no color” button was at the bottom of the color palette on the left for an achromatic color experience.

2.3 Materials and Design

To examine whether specific linguistic factors were related to synesthetic color similarity, we used a set of Chinese characters including 803 characters that allowed us to make critical comparisons. There were eight sets of Chinese characters in this study, as described below. The complete material list is in the Appendix 2.

Set1. Thirty-nine pairs of semantically related characters without radical repetition were selected from Chou, Chen, Wu, and Booth (2009), by removing nine semantic relatedness pairs with opposite meanings from the original list of 48 pairs. These characters were previously judged for the relatedness of meanings by university students.

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In the current study we also asked the synesthetes in this experiment to judge the perceived semantic relatedness after the whole experiment ended.

Set 2 and Set 3. Twenty radicals were selected to further investigate the effect of sharing the same radicals and with transparent or opaque semantic relatedness. These characters were adopted from Y.C. Chen and Yeh (2017). The radical function was classified as transparent or opaque according to whether the meaning of a given character is congruent with the meaning of its radical or not. There were two characters with semantically transparent and one character with semantically opaque selected for each radical. That is, for each radical, there was one transparent-transparent pair (Set 2) and two transparent-opaque pairs (Set 3). The transparent-transparent pairs had high semantic relatedness and transparent-opaque pairs had low semantic relatedness.

Set 4. There were 63 pairs of characters sharing the same pronunciation but no repeated radicals in this set. Since Mandarin Chinese is a tonal language, the tone sameness was also matched in each pair.

Set 5 and Set 6. There were 56 pairs of characters with the same phonetic radicals, 26 pairs with the same pronunciation (Set 5) and 30 pairs without sharing the same initial or final phoneme (Set 6).

Set 7 and Set 8. Forty binding words including two characters nearly always appear together were selected. Twelve were character pairs sharing unrelated pronunciation (Set 7) and 28 with at least one shared phoneme (Set 8).

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In addition to the eight sets manipulated, other characters were selected as fillers to (1) increase the external validity of comparing the interested character pairs with randomly selected character pairs and (2) obscure the purpose of the experiment so as to avoid response biases from the participants.

2.4 Procedure

A modified standardized Synesthesia Battery (Eagleman et al., 2007) was used for the color matching process. Since the experiment was very time consuming, the materials were randomized and separated into four to five blocks including 100~200 characters per block for each participant. Every time one participant came to the laboratory for 1~2 hours for experiments by appointment to finish one block, until they finished all the trials.

In each trial, the participant was provided one black character on the bottom and a color palette on the top of the screen (see Figure 1). The participant was asked to choose his/her synesthetic color of the presented stimuli by clicking the mouse directly on the palette, and the chosen color would be presented on the right side of the palette. The brightness of the palette was adjustable by pressing left- or right-bottom to make it darker or brighter. A button of “no color” was shown on the bottom of the palette and it was meant to be pressed in case the stimulus did not induce any synesthetic color. Participants were not limited to the time of choosing, and once they decided the color, they could press the space key to continue to the next trial. For some participants, one character could induce more than one color. We asked participants to press the "a" instead of the "space" key if they saw other colors induced by the subpart of characters and then choose the color from the palette. If they only perceived synesthetic colors induced by the subparts of character but no color was perceived by the whole character, they chose "no color

doi:10.6342/NTU201903697

"first, and pressed "a" to select colors for the subpart. Once they finished choosing the additional colors, they press back to "space" to continue to the next trial.

2.5 Data Analysis

For each participant, data from characters inducing no synesthetic color or only inducing color by its subpart would be excluded from further analysis. Each RGB value of collected synesthetic color was transformed into CIE L*a*b* space. In the CIE L*a*b* color space, a given spatial distance corresponds to an equivalent perceptual difference. In other words, one unit in this color space is approximately equal to one just-noticeable difference (JND) in psychological scale.

We analyzed the distribution of synesthetic color in the color space with spatstat (Baddeley, 2008), an R package for spatial point pattern analysis. While we assumed some synesthetic color points were closer to each other than others, we analyzed the "interpoint interaction", which is stochastic dependence between the points in a point pattern (Baddeley, 2008). Three patterns can be identified as "regularity", "clustering", or "independence" based on whether the points tend to avoid each other, be closer together than a Poisson process, or close to a Poisson distribution. To be more specific, we applied *L*-function (computed from Ripley's *K* function, which is used for descriptive statistics for detecting deviations from spatial homogeneity. See details in Hamada et al., 2016) to decide which type of the pattern is for the distribution of the synesthetic colors we obtained from the synesthetes.

The Euclidean distances between each pairs of synesthetic colors were calculated as color differences. The average distances of all the possible pairs between characters for each participant were set as the baseline, which was also considered as the expected value of distances between randomly sampled characters.

doi:10.6342/NTU201903697

For each pair of synesthetic colors, we calculated the *Color Similarity Index (CSI)* by subtracting the distance between given pairs from the baseline. In this index, zero means no difference in color between a given pair and random sampling, and higher values indicate higher similarity of synesthetic colors. We calculated, at both subject-level and group-level analyses, the average CSIs for each linguistic factor (semantics, phonology, orthography, and morpheme) as mentioned before.

To test the hypothesis of whether an interested factor was related to the similarity of synesthetic color, we applied a Monte-Carlo resampling method to estimate whether the average distance of specific character pairs was significantly different from the average distance of randomly sampled pairs (baseline). Since for each participant, a large amount of synesthetic colors from Chinese characters were collected, comparing the sample mean and the confidence interval of resampling data was considered to be a better estimation of the real distribution of color difference. The number of valid pairs of characters (removing pairs consisting of the excluded characters) in each character set were used as a resampling sample size. From the pool of all finally included characters, we calculated the mean color difference of resampled pairs and repeated 9999 times to get the distribution of mean difference. The Monte-Carlo p-value of the one-tailed test (only high similarity was predicted) was the ranking of the average distance of specific character pairs in this distribution divided by 10000. The significance level was set at alpha $< .05$. In the group-level analysis, the mean CSI of each condition was compared with zero using bootstrapping one-tailed one-sample t-test (BCa, $N = 10000$) to see whether a factor predicts high similarity in general.

To make possible the comparison between different character sets, we also adopted linear mixed-effects analyses using the 'lme4' package for R. The value of CSI between each pair was treated as a dependent variable. According to Hamada, Yamamoto, and

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Saiki (2017), the contributions of different linguistic factor may differ across individuals. We first create a full model with all fixed effects (similar pronunciation, semantic relatedness, semantic radical repetition, and phonetic radical repetition) and two fixed interaction terms (phonetic radical repetition × similar pronunciation, semantic radical repetition × semantic relatedness). All the six factors included in fixed effects were also included in two random effects term (subject and character pairs). We then reduced the model by testing each random-effect term and removed terms based on likelihood ratio tests of model reduction. A new model was fitted with preserved random effect and four fixed effects (without interaction terms) to test the main effect by comparing with a reduced model without the fixed effect in question (i.e., similar pronunciation, semantic relatedness, semantic radical repetition, or phonetic radical repetition). The interaction effect was tested by comparing the previous new model plus the two fixed interaction terms and reduced models without one of the interaction terms. We performed post-hoc interaction analysis by using ‘emmeans’ package to see the simple main effect under the interested interactions.

As we mentioned above, the contributions of different linguistic factor may differ across individuals, which could be partially explained by various subjective synesthetic experience (i.e., associator-like or projector-like; Hamada et al., 2017). We performed a Pearson correlation analysis to test the correlation between the random slopes and scores of the synesthetic experience (ISEQ-scale in this study) to see whether a factor would contribute differently according to different types of synesthetic experience.

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3. Results

In Figure 2(a) and 2(b) we provide an example of the density plots in both the 3D CIE L*a*b* color space and the 2D a*b* chromaticity plane. We also depict the L function in Figure 2(c) derived from Figure 2(b) to visualize whether the synesthetic color distribution was more clustered than a random selection from the Munsell re-notation data for each participant.

Appendix 2 shows the total number of collected data and valid pairs, which was critical for the set size of baseline calculation and resampling size of the Monte-Carlo method. The CSI was calculated for each set of character pairs and for each participant respectively. The mean CSI of all participants was also provided. Figure 3 to Figure 7 show the CSI calculated for each participant and the group mean with different linguistic factors respectively. Figure 8 and Table 2 show the mean CSI and the results of linear mixed effect analysis, respectively.

3.1 Distribution of Synesthetic Color in CIE L*a*b Color Space

As we hypothesized that the synesthetic color was clustered in the color space based on some linguistic factors, we first examined whether or not the synesthetic color is randomly distributed in color space. In other words, for each participant, we examined the synesthetic color distribution in the CIE L*a*b color space. All of the participants showed some high-density region of color point distribution, suggesting that the synesthetic color was clustered indeed. A statistical confirmation was provided in the L-function graph (shown in Figure 2 as an example from one participant), which describes the point patterns for synesthetic colors at a distance r from a given point for each synesthetes. All the *L*-function of each synesthetes showed a constant positive value, at

doi:10.6342/NTU201903697

the same time larger than 95% of random selection from random selection of Munsell re-notation, implying that the synesthetic color are clustered in the CIE L*a*b* color space, and also more clustered than random selection.

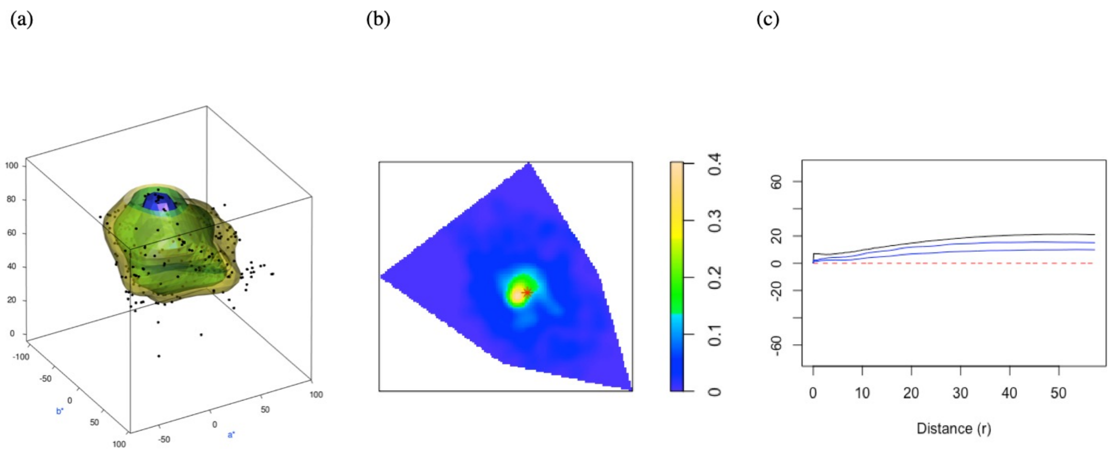

Figure 2. An example of spatial distribution of synesthetic colors in the CIE L*a*b* (1976) uniform color space based on the data collected from synesthete YHC. (a) Density plots of the synesthetic colors in the CIE L*a*b* color space, as estimated by kernel estimation for synesthete YHC. (b) Density plots of the synesthetic colors in the a*b* chromaticity plane for synesthete YHC. (c) *L* functions of the point patterns for chromatic synesthetic colors at a distance r from a given point for synesthete YHC. The solid black lines indicate the computed *L* function, and the interval between the two blue lines indicates the 95 % confidence interval for complete spatial randomness (CSR). Specifically, many spatial point patterns (1,000) randomly selected from the Munsell re-notation data can be generated under CSR, and Ripley's *K* function can be estimated for each participant (see Appendix 3. for the *L* functions for each participants).

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3.2 Semantically Related Characters Without Repeated Radicals (Set1)

Here, we analyzed color similarity of pairs of characters that are semantically related. The results of CSI analysis are shown in Figure 3. In general, semantic relatedness did predict some level of synesthetic color similarity. The subject-level analysis exhibited that four out of 11 participants showed significance of CSI and random sampling (CCD: CSI = 11.29, Monte-Carlo p = .0002 YPW: CSI = 27.54, Monte-Carlo p = .0004 CLC: CSI = 11.92, Monte-Carlo p = .0101 HLC: CSI = 32.19, Monte-Carlo p = .0007). Group-level analysis showed a marginally significant effect of semantic relatedness (mean CSI = 9.13, p = .069, 95% CI with 10000 replications [3.11, 16.86], zero not included).

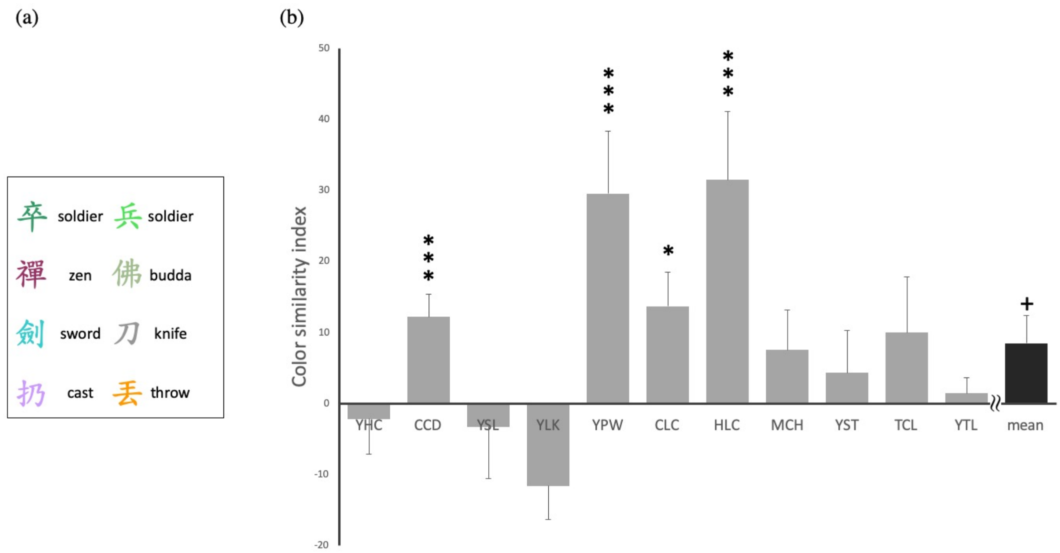

Figure 3. Results of color similarity for semantically related characters without repeated radicals. (a) Examples of colors of semantically related character pairs from synesthete YHC. Character pairs in this set shared similar meaning without repeated radicals; (b) Color similarity index (CSI) for each participant and their group mean. The error bars represent one standard error from the mean.

* $p < .05$. ** $p < .01$. *** $p < .001$. + $p < .10$.

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Since four participants were more likely to perceive similar color for semantically related characters and this trend was also marginally significant at the group-level analysis, we consider semantic relatedness alone could influence synesthetic color correspondence. The next two groups of characters could further confirm this conclusion.

3.3 Transparent-transparent (Set 2) and Transparent-opaque (Set 3) Semantic Pairs

We analyzed how radical repetition and semantic relatedness affect synesthetic color similarity. Our results showed that, in general, same semantic radical predicted well in synesthetic color similarity, especially when they were highly semantically related; that is, transparent-transparent semantic pairs. At the subject-level analysis, we found that pairs with two transparent characters showed a significant higher CSI than random sampling in nine out of 11 participants (Appendix 1). On the other hand, for pairs with one transparent character and one opaque character, five out of 11 participants showed a significant higher CSI.

At the group-level analysis, only Set 2 showed a significant higher CSI than zero (Transparent-transparent pairs: mean CSI = 19.87, p = .004, 95% CI with 10000 replications [14.11, 26.29]. Transparent-opaque pairs: mean CSI = 5.17, p = .098, 95% CI with 10000 replications [-0.88, 11.37], zero included). The CSIs of transparent-transparent pairs were also significantly higher than transparent-opaque pairs (mean CSI difference = 14.70, p = .063, 95% CI of difference between group with 10000 replications [7.37, 22.83]). To sum up, a higher difference in the validity of semantic radicals (opaque or transparent) could predict a more different synesthetic color, indicating that the transparency of semantic radical influenced the synesthetic color mapping.

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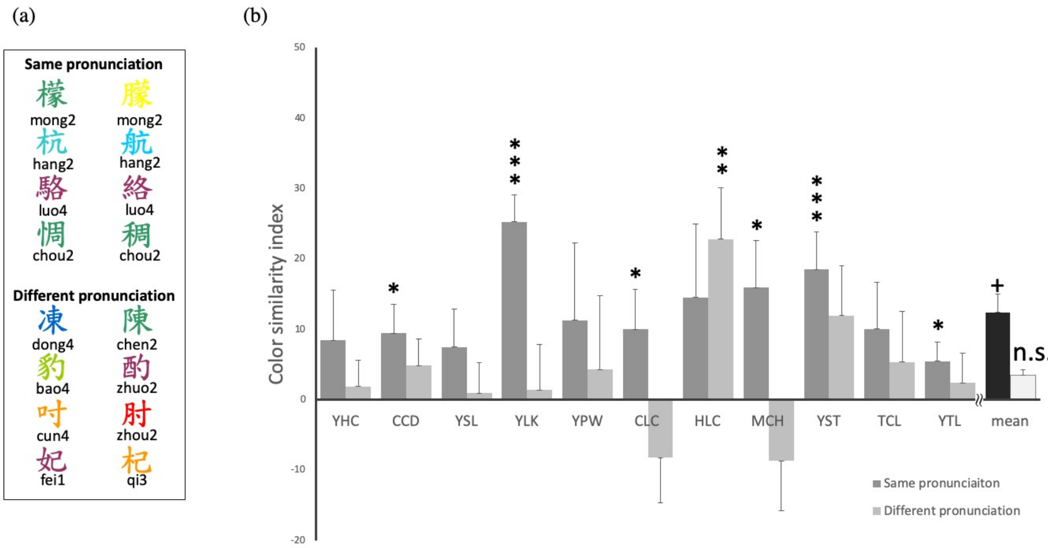

Figure 4. Results of characters with the same semantic radicals but differing in semantic transparency. (a) Characters with a synesthetic color selected from synesthete YHC. In the first and second columns are characters with a transparent semantic meaning of radicals, which are highly semantically related; in the third column are characters with an opaque semantic meaning of radials, which provide a lower semantic relatedness between this column and the other two. (b) Color similarity index (CSI) for each participant and their group mean. The error bars represent one standard error from the mean.
* $p < .05$. ** $p < .01$. *** $p < .001$. + $p < .10$.

3.4 Homophone Pairs Without Repeated Radicals (Set 4)

The results of CSI analysis for the synesthetic color similarity for character pairs sharing the same pronunciation are shown in Figure 5. In general, the same pronunciation did not predict well the synesthetic color similarity. The subject-level analysis exhibited that three out of 11 participants reached statistical significance (CCD: CSI = 6.23, Monte-Carlo p = .012 YLK: CSI = 9.13, Monte-Carlo p = .004 YST: CSI = 35.73, Monte-Carlo p < .0001). The group-level analysis showed no significant difference from zero (mean CSI = 2.95, p = .466, 95%CI with 10000 replications [-3.59, 10.80], zero included).

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Although one synesthete, YST, did subjectively perceive similar color for characters with the same pronunciation, other synesthetes showed minor or a random level of color similarity for these homophone pairs. Although individual difference existed, the phonological factor seems not to play a major role compared to other linguistic factors we manipulated.

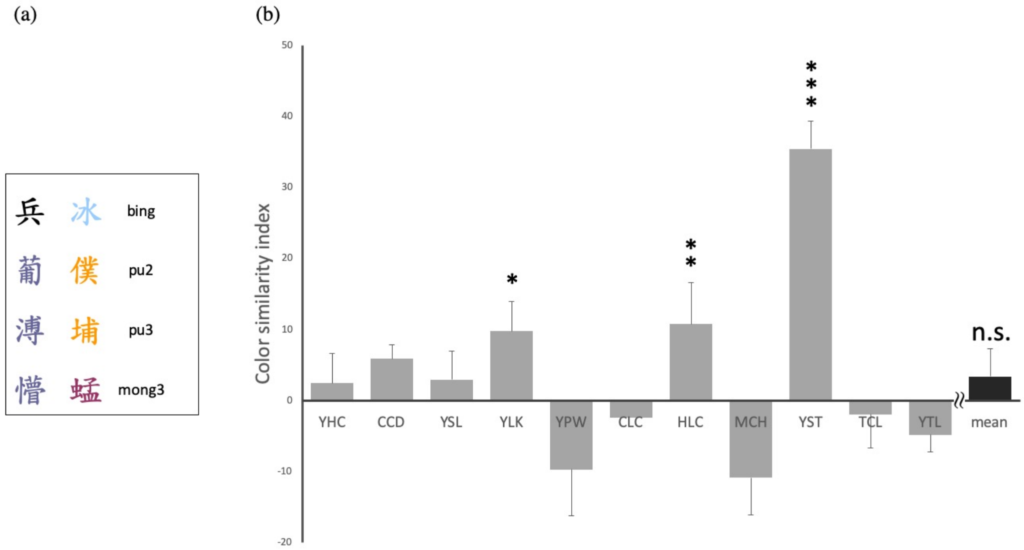

Figure 5. Results of characters with the same pronunciation. (a) Examples of colors of homophone pairs from synesthete YHC. Character pairs in this set shared identical pronunciation without repeated radicals. (b) Color similarity index (CSI) for each participant and their group mean. The error bars represent one standard error from the mean.

* $p < .05$. ** $p < .01$. *** $p < .001$. + $p < .10$.

3.5 Phonologically Related Characters with Repeated Phonetic Radicals (Set 5 and Set 6)

The same phonetic radical, in our data, only predicted similarity of synesthetic color only when the characters also shared the same pronunciation. At the subject-level analysis, we found that pairs with the same pronunciation (Set 5) showed a significant higher CSI in six out of 11 participants (Appendix 1). On the other hand, for pairs with

doi:10.6342/NTU201903697

different pronunciation (Set 6), only one out of 11 participants showed a significant higher CSI than zero.

At the group-level analysis, only Set 5 showed a significant higher CSI than zero (Same pronunciation: mean CSI = 14.52, p = .074, 95% CI with 10000 replications [10.20, 19.45]. Different pronunciation: mean CSI = 2.59, p = .383, 95% CI with 10000 replications [-2.06, 8.47], zero included). The CSI of the characters with the same phonetic radical and pronunciation was also significantly higher than the CSI of characters in the different pronunciation group (mean CSI difference = 11.93, p = .046, 95% CI of difference between group with 10000 replications [5.36, 19.01]).

Again, the analysis of Set 5 and Set 6 showed that the validity of phonetic radical function affected the synesthetic color mapping. With different pronunciations of the characters, characters sharing the same phonetic radical did not lead to higher color similarity.

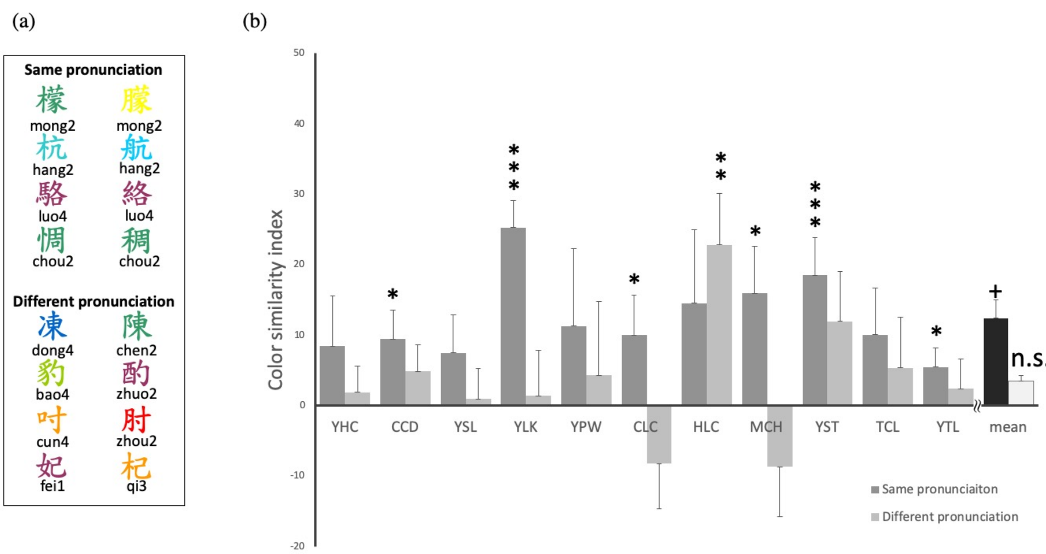

Figure 6. Results of characters with the same phonetic radicals but differing in their phonological relatedness. (a) Characters with a synesthetic color selected from synesthete YHC. The first group were character pairs with the same phonetic radical and the same pronunciation; the second group were character pairs with different pronunciations. (b)

doi:10.6342/NTU201903697

The results of Color similarity index (CSI) for each participant and their group mean. The error bars represent one standard error from the mean.
* $p < .05$. ** $p < .01$. *** $p < .001$. + $p < .10$.

3.6 Binding Words (Set 7 and Set 8)

Regardless of various similarity in their pronunciations, the character pairs from binding words had significantly higher CSIs in nearly all synesthetes at the subject-level analysis (Appendix 1, except for YST in the group of unrelated pronunciations and YLK in the group of related pronunciations) and the group-level analysis (Table 2). The difference between these two sets was non-significant.

At the group-level analysis, both Set 7 and Set 8 showed a significantly higher CSI than zero (Related pronunciation: mean CSI = 24.21, $p = .002$, 95% CI with 10000 replications [16.03, 32.98], zero not included. Unrelated pronunciation: mean CSI = 23.65, $p = .002$, 95% CI with 10000 replications [15.24, 32.41], zero not included). No significant difference was found between CSI of Set 7 and Set 8 (mean CSI difference = 0.56, $p = .865$, 95% CI of difference between group with 10000 replications [-4.59, 6.20], zero included).

Three points worth mentioning in the analysis of Set 7 and Set 8. First, although without a completed meaning, individual characters in the binding words can still elicit synesthetic color perception. Second, color similarity was generally higher for binding words than other character pairs. Third, similarity of pronunciation seemed not affect the synesthetic color mapping of binding words.

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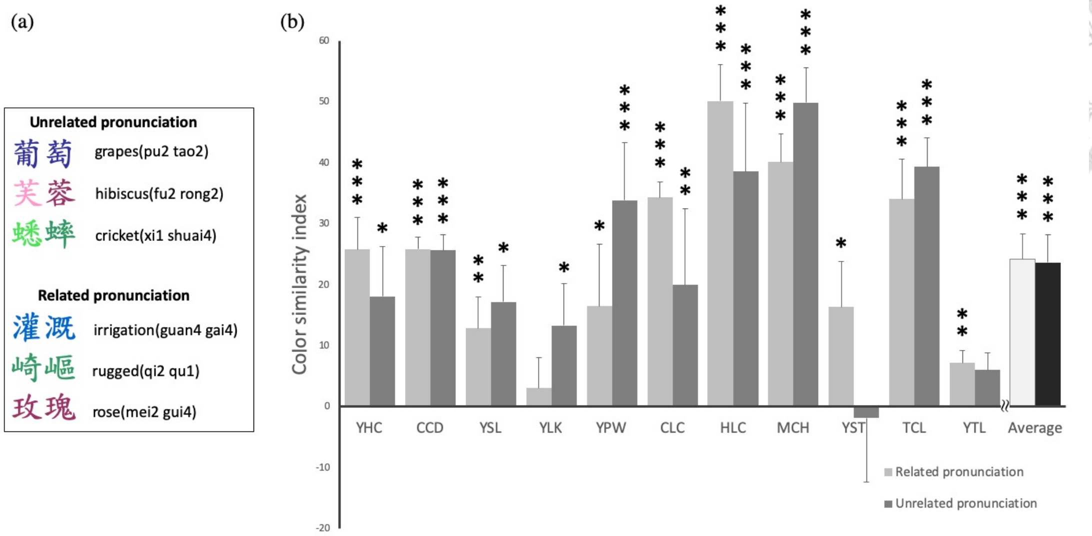

Figure 7. Results of binding words formed by two characters with a single morpheme. (a) Examples of binding words selected by synesthete YHC. Character pairs in this set are monomorphemic compounds. The first group are characters without similar phoneme; the second group are characters shared either one or two phonemes; (b) Color similarity index (CSI) for each participant and their group mean. The error bars represent one standard error from the mean.

* $p < .05$. ** $p < .01$. *** $p < .001$. + $p < .10$.

3.7 Linear Mixed Effect Model Analysis

In the linear mixed-effects analysis, the preserved random effect terms included two random intercepts for subjects and character pairs, four random slopes (pronunciation, semantic relatedness, repetition of semantic radical and repetition of phonetic radical) for subjects, based on likelihood ratio tests of model reduction. This result indicated that the contributions of different linguistic factor differ across individuals.

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Table 2

Summary of group-level analysis of all the results. Mean CSI and mean Difference between critical conditions, values in parentheses indicate standard errors.

	CSI (SE)	*p*-value	$95\%CI_{BC}$	Df (SE)	*p*-value	$95\%CI_{BC}$
No Repeated Radicals						
Semantic Related	9.13 (3.48)	.069	[3.11, 16.87]	10.74 (3.02)	.010	[4.62, 17.76]
Repeated Sematic Radicals						
High Semantic Relatedness (T-T)	19.87 (3.29)	.004	[14.11, 26.29]	14.70 (4.62)	.063	[7.37, 22.83]
Low Semantic Relatedness (T-O)	5.17 (2.68)	.098	[-0.88, 11.37]			
No Repeated Radicals						
Same Pronunciation	2.95 (3.80)	.466	[-3.60, 10.80]	11.57 (2.18)	.005	[6.75, 17.02]
Repeated Phonetic Radicals						
Same Pronunciation	14.52 (3.10)	.074	[10.20, 19.45]	11.93 (4.09)	.046	[5.36, 19.01]
Different Pronunciation	2.59 (2.26)	.383	[-2.07, 8.48]			
Binding Words						
Unrelated Pronunciation	24.21 (4.16)	.002	[16.03, 32.98]	0.55 (3.15)	.865	[-4.58, 6.20]
Related Pronunciation	23.65 (4.60)	.002	[15.25, 32.41]			

Note. CSI = Color Similarity Index; T-T = Transparent – Transparent ; T-O = Transparent – Opaque.

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The main effects showed that the contribution from all the linguistic factors we manipulated was significant, including semantic relatedness [$\chi^2(1) = 6.582$, $p = .010$], repetition of semantic radical [$\chi^2(1) = 10.811$, $p = .001$], pronunciation [$\chi^2(1) = 4.4429$, $p = .035$], and repetition of phonetic radical [$\chi^2(1) = 7.8154$, $p = .005$]. The interaction between pronunciation and phonetic radical repetition was significant [$\chi^2(1) = 3.5147$, $p < .001$], which suggests that the addition of phonetic radical repetition × similar pronunciation improved the model. The interaction between semantic relatedness and semantic radical repetition was not significant [$\chi^2(1) = 1.5559$, $p = .21$]. The contrast of pronunciation similarity was significant when phonetic radical was repeated ($p = .001$), but not significant when phonetic radical was not repeated ($p = .145$).

We have also attempted to include character occurrence frequency difference and stroke number difference as factors of both random and fixed effects, because frequency effect was found important for English alphabet synesthetic color similarity (Watson et al., 2012) and varied based on individual differences (Hamada et al., 2017). However, the inclusion of character frequency difference did not significantly improve the model for both random effects by subject ($p = .912$) and fixed effects ($p = .296$) in our study of Chinese character.

The fixed effect of the final model was shown in Table 3. The estimate of semantic relatedness and semantic radical repetition were also higher than pronunciation similarity and phonetic radical repetition, indicating a relatively larger contribution of semantic relatedness than phonological relatedness

doi:10.6342/NTU201903697

Table 3

Results of linear mixed effects models on different linguistic factors and color similarity index (CSI)

Predictor	**Estimate**	**SE**	***t*-value**	***p*-value**
Intercept	-3.031	3.557	0.852	0.407
Pronunciation Similarity	5.430	3.284	1.654	0.117
Phonetic Radical Repetition	5.330	3.484	1.530	0.133
Semantic Relatedness	12.765	4.515	2.827	0.015
Semantic Radical Repetition	9.701	2.572	3.771	0.001
Pronunciation Similarity × Phonetic Radical Repetition	7.007	3.723	1.882	0.060

3.8 Correlation Analysis

To further reveal the relationship between the effect of a given linguistic factor and its corresponding subjective synesthetic experience, we also calculated the correlation coefficient between ISEQ-scores and random slopes for each linguistic factor. The results showed that ISEQ-score was significantly correlated with pronunciation (*Pearson's r* = .663, *p* = .026), indicating that the effect of pronunciation was larger when the synesthete was more associator-like. The correlation was not significant between ISEQ-score and semantic relatedness (*Pearson's r* = .118, *p* = .730), phonetic radical repetition (*Pearson's r* = .148, *p* = .663), and semantic radical repetition (*Pearson's r* = -.178, *p* = .601).

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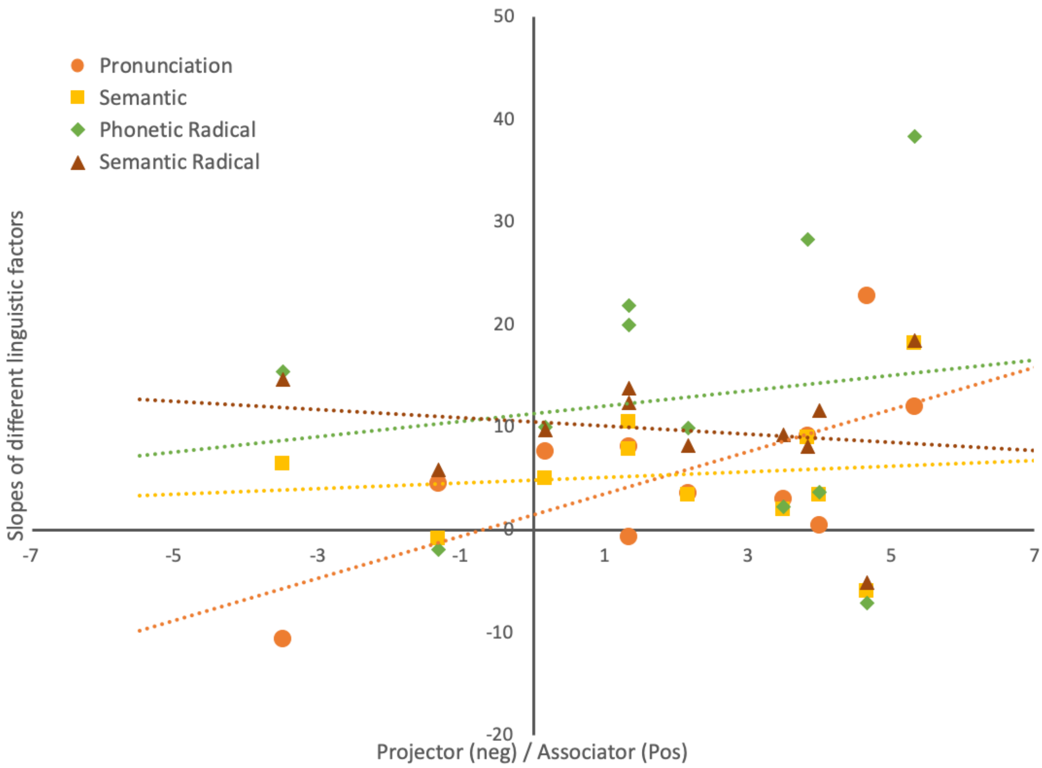

Figure 8. Relation between slopes and scores of the subjective synesthetic experience for different linguistic factors

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4. Discussion

We examined eight sets of perceived color of Chinese characters from Taiwanese synesthetes to clarify how different linguistic factors related to the synesthetic color similarity. Together, we conclude that (1) Fulfillment of Chinese radical function played an important role in Chinese synesthetic color mapping. With repeated semantic or phonetic radical, the difference in color similarity between semantic and phonetic relatedness was higher than without repeated radicals (see Table 2). (2) For grapheme-color synesthesia in Chinese, the synesthetes tended to have higher color similarity for semantic relatedness character pairs than for phonological relatedness pairs, indicating the importance of meaning than sound in logograph Chinese. A summary of group CSI mean of each set is provided in Figure 9.

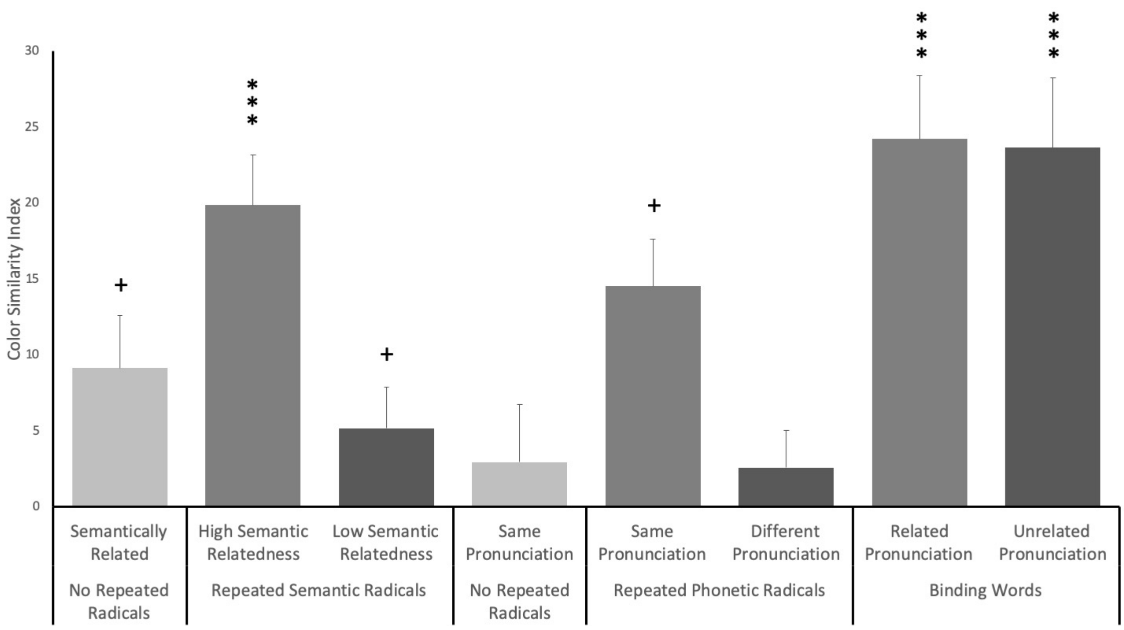

Figure 9. Results of mean color similarity index of each character set. The error bars represent one standard error from the mean.

* $p < .05$. ** $p < .01$. *** $p < .001$. + $p < .10$.

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4.1 Semantic Relatedness

In the following paragraphs, we compare the linguistic factors contributing to the synesthetic coloring of Chinese and other languages and discuss the underlying psycholinguistic mechanisms causing the similarity or difference in synesthetes' color percepts.

We found that semantic relatedness is related to the similarity of synesthetic color, mainly supported by the influence of semantic transparency of radicals. This conclusion is consistent with other findings showing the influence of the typical colors related to word meanings (e.g., blue color for the word "sky") in both alphabetic languages (Barnett et al., 2008; Rich et al., 2005) and logographic languages (Asano & Yokosawa, 2012).

Semantic mechanisms have been considered responsible for many forms of synesthesia (for review, see Mroczko-Wąsowicz & Nikolić, 2014), not only grapheme-color synesthesia, but also colored sequence (color percepts triggered by ideas of weekdays or months; Simner, Mulvenna, et al., 2006), spatial sequence synesthesia (visualization of numerical sequences in physical space; Kadosh & Gertner, 2011), lexical-gustatory synesthesia (tastes triggered by words; Ward & Simner, 2003; Ward et al., 2005), or even swimming-style synesthesia (color percepts triggered by swimming styles; Nikolic, Jurgens, Rothen, Meier, & Mroczko, 2011). The conceptual component, instead of purely sensory inputs, is recognized in many forms of synesthesia as the inducer. Because each Chinese character or radical represents a specific meaning in our mind, it is highly possible that the concept associated with each Chinese character or radical plays an essential role in Chinese-color synesthesia.

Compared to the role of phonology processing, semantic processing can be a more discriminating feature in Chinese character recognition and thus grapheme-color synesthesia, and radical meaning interacts with the whole character recognition. In the

doi:10.6342/NTU201903697

traditional model of hierarchical word processing (Perfetti & Tan, 1998), processing of orthography is followed by phonology and then meaning. However, recent evidence has shown that semantic meaning can be accessed directly from orthography in Chinese word reading (Yan, Richter, Shu, & Kliegl, 2009; Yan, Zhou, Shu, & Kliegl, 2012; Zhang, Xiao, & Weng, 2012). Yeh and colleagues have also shown that under visual crowding (Yeh, He, & Cavanagh, 2012; J. Zhou, Lee, & Yeh, 2016) and continuous flash suppression (Yang et al., 2017; Yang & Yeh, 2011) semantic meaning of Chinese characters could still be accessed without orthography recognition. Y.C. Chen and Yeh (2015); Yeh and Li (2002, 2004) also found that radicals are processed earlier than characters and the function of radicals, be it semantic or phonetic, affects character recognition.

4.2 Pronunciation Similarity

Surprisingly, pronunciation was not strongly related to the synesthetic color similarity, a result quite different from previous studies in alphabetic/phonetic languages (Kang et al., 2017) and logographic characters in Japanese (Asano & Yokosawa, 2012), but in line with the results of Chinese characters (Simner et al., 2011). This may be related to the characteristics of Chinese. As we mentioned in the Introduction, homophones are quite common in Chinese, and pronunciation is not regularly related to the composition of characters. Without semantic context, it is hard to acquire the meaning of a syllable in Chinese. This result also echoes other studies of Chinese processing and first-language acquisition. H.C. Chen and Shu (2001) showed that the semantic priming effect of Chinese characters recognition appeared at different SOAs, while homophonic priming had negligible effects, suggesting that phonological information is optional but not mandatory for Chinese character recognition.

doi:10.6342/NTU201903697

From the view of the development of language acquisition, pre-school children notice the fact that characters with the same pronunciation but different meanings are more likely to look different in their shapes. More than 86 % of second-grade students are using a complicated semantic-phonological principle to discriminate whether two same-pronunciation syllables are represented by the same characters (e.g. the words 公雞 ([gong1 ji1], "rooster") and 母雞 ([mu3 ji1], "hen") are written with the same character 雞([ji1], "chicken"), but the word 飛機([fei1 ji1], "airplane") is written in a different character 機([ji1], "machine"); S.Y. Chen, 2000).

Still, phonological similarity was found to be related to the similarity of the synesthetic color of graphemes in alphabetic systems (Kang et al., 2017; Shin & Kim, 2014). Moreover, phonetic spelling system was also found to be related to the synesthetic coloring of words (Baron-Cohen, Harrison, Goldstein, & Wyke, 1993; Mills et al., 2002; Simner, Glover, et al., 2006; Ward et al., 2005). It is a tricky question to categorize whether a Chinese character is at grapheme level or word level, because some words consist of two characters and sometimes only one character. Also, characters such as most of the phonograms can be subdivided into different radicals that both have their meanings when standing alone. Having said that, it is still possible to compare our results to each level of those studies. For example, Asano and Yokosawa (2013) presented a comprehensive model of grapheme-color association, which explained that the difference of grapheme-color associations between two writing systems is based on how graphemes are processed in the brain and how they are introduced during an individual's development. Since Asano and Yokosawa also proposed that a synesthetic color highlights the most discriminating feature of each grapheme, it is not surprising that pronunciation is not a determining factor to facilitate discrimination of Chinese

doi:10.6342/NTU201903697

characters. The model also supports the results of Simner et al. (2011), in which synesthetes who speak Chinese as a second language also exhibited synesthetic coloring influenced by the initial letter or vowel.

Also, if we consider that a Chinese character is somewhat at the word-level of processing, the phonetic function of radicals is still not a good predictor of the whole word's pronunciation (recall that only 29% of phonetic radicals are related to the pronunciation of their belonging characters). So even if the synesthetic colors of radicals are related to the whole characters, it might not be directly related to the pronunciation.

4.3 Orthographic Similarity

The synesthetic color similarity was also shown in characters with the same radical but not semantically related (i.e., the transparent-opaque pairs), in which we should consider the morphological representation of semantic radicals. Our finding of radical identity is in line with studies of synesthetic color mapping in other languages, in which letter-to-word coloring is systematically related (Barnett, Feeney, Gormley, & Newell, 2009; Mills et al., 2002; Simner, Glover, et al., 2006; Ward et al., 2005). The synesthetic color similarity was found in shape similarity in English alphabets (Watson et al., 2012; but not in Japanese and Arabic letters; see Asano & Yokosawa, 2011; Van Leeuwen, Dingemanse, Todil, Agameya, & Majid, 2016). In another study on word-level synesthesia of lexical-gustatory synesthesia, pseudo-words tended to trigger more similar taste perception when they are orthographically close to words, regardless of the semantic representation (Simner & Haywood, 2009).

Studies have shown that radicals are represented by orthographic identity and serve as orthographic inputs to the representations at the character level (Y.C. Chen & Yeh, 2017; Feldman & Siok, 1999; Perfetti, Liu, & Tan, 2005; Taft, 2003). Also, a radical can

doi:10.6342/NTU201903697

further activate its associated meaning that would likely interact with the character meaning. Feldman and Siok (1999), for example, They found that the priming effect of character recognition within 43 ms was a linear summation of the effect of sharing related meanings and the effect of sharing the same semantic radical between the prime and the target. This effect, however, was decreased when the prime was presented longer (i.e., 243 ms) if the characters with the same radicals were not semantically related. Thus, while considering the interaction between radicals and whole-character synesthetic coloring, both semantics and radical repetition between characters could play a role.

4.4 Morpheme

In this study, we considered the second-order color relationship for synesthetic colors of Chinese compound words. We found that similar synesthetic colors were elicited by characters from the same binding words (葡萄) without their being appearing at the same time (i.e., the participants viewed these characters one after another in a random order), and this finding provides some convergent evidence of several psycholinguistic findings of Chinese processing. First, while single characters from binding words do not make a complete meaning, they are still sufficient to elicit the synesthetic color perception. All our participants stated that they did not perceive a uniform color while seeing a binding word (i.e., they saw two characters at the same time in the interview after the whole experiment). Instead, they reported two similar but not identical colors (e.g., synesthete YHC perceived purple for both "葡" and "萄," while subjectively felt brighter color for the first character than the second one). In the studies of English words of synesthetic color, compound words usually elicit one color determined by the color of the first letter, sometimes with an additional color (Blazej & Cohen-Goldberg, 2016; Mankin, Thompson, Branigan, & Simner, 2016) in compound

doi:10.6342/NTU201903697

words. However, our study supports that the level of compound word processing in English is probably more similar to the level of single Chinese character (at least in phonogram) processing rather than Chinese compound words. This viewpoint could also be supported since we also had four participants (YPW, YLK, YST, TYK) who sometimes reported to perceive a separated color from the sublexical parts (e.g., when looking at the character 礁 ([jiao1], "reef"), YLK saw olive yellow for the whole character; at the same time, she also saw lead gray and mineral green for the semantic radical 石([shi2], "rock") and the phonetic radical 焦([jiao1], "scorched"), respectively). Second, although with slight differences, the high similarity of synesthetic color from the characters of the same binding words is still robust across different synesthetes. Because the result is not significantly affected by similarity in pronunciation, it is related more to both morphological and semantic factors, which are inseparable in this case.

4.5 Individual Difference

In our results of linear mixed effect analysis, we found that the inclusion of random slopes (pronunciation similarity, semantic relatedness, repetition of semantic radicals and phonetic radicals) by subjects would improve the model comparing to those model without these random effect, suggesting that individual difference did contribute to the effect of different linguistic factors we manipulated here. Watson et al. (2012) showed that although three correlations (shape similarity-hue difference, ordinary difference-hue difference, letter frequency-luminance difference) were positive for a majority of synesthetes, not all participants showed the significance of these correlations (only 30% of synesthetes had positive correlations for all three mappings). Hamada et al. (2017) also showed that contributions of grapheme factors differed across individuals, and could be partially explained by the type of synesthetic experience (shape difference was associated

doi:10.6342/NTU201903697

with projector synesthetes, while ordinality and familiarity associated with associator synesthetes). In our study, however, only pronunciation similarity was found to be associated with associator-type synesthete. One more interesting finding in our study is that the two projector-type synesthetes reported a higher proportion of perceiving additional color from the sublexical part of a character. These findings could be parsimoniously explained by considering projector as a more "low-level" type of synesthesia that the color mapping could rely more on perceptual-level information, while processing of phonology was after orthographical processing in Chinese character recognition. Evidently, individual difference is an intriguing future direction await further investigations.

Together, our results provide a better understanding of synesthesia in Chinese, which also yields us to know more about the nature of synesthesia. In the study of Chinese synesthesia, factors from lexical, sublexical, and even higher-level semantics all contribute to part of the synesthetic color formation. While studies of English lexical synesthesia showed a rather clear correlation between the first letter and the whole word synesthetic color, in Chinese, no one single factor could exclusively determine synesthetic color mapping, suggesting that synesthesia is a phenomenon that involves multiple levels of language processing.

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5. Conclusion

In this study, we found that semantic relatedness and orthographic similarity (repeated semantic radicals and repeated phonetic radicals) played important roles in synesthetic color similarity. Semantic relatedness seems to be the most critical factor that determine the synesthetic color similarity we obtained here, because the most similar colors came from character pairs from binding words that form a single morpheme, in addition to similar colors obtained from semantic related character pairs with or without sharing semantic radicals. Phonetic similarity was correlated with synesthetic color similarity only when two characters shared the same phonetic radical, but not when no repeated phonetic radical existed between two characters. Compared to most studies of English grapheme-color synesthesia, the current study provides a comparison basis. Together, synesthetic colors were found to be influenced by systematic rules varied across language, and these rules are based on existing psycholinguistic mechanisms from different levels of language processing.

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Appendix 1. Summary Table of Color Similarity Index (CSI) for Each Synesthete

	Subject	YHC	CCD	YSL	YLK	YPW	CLC	HLC	MCH	YST	TCL	YTL
No Repeated Radicals	AP	35	36	37	38	39	40	41	42	43	44	45
Semantic Related	CSI(SE)	-1.47(4.77)	11.29(3.19)	-5.65(7.26)	1.55(4.75)	27.54(8.81)	11.92(5.01)	32.19(9.62)	6.89(5.57)	4.64(6.00)	10.04(7.85)	1.45(2.23)
	p-value	.6268	.0002***	.8566	.3695	.0004***	.0101*	.0007***	.1309	.2095	.0599	.2912
Repeated Semantic Radicals	AP	19	20	21	22	23	24	25	26	27	28	29
High Semantic Relatedness	CSI(SE)	13.02(4.53)	16.70(2.47)	9.77(8.78)	18.49(2.30)	26.11(9.41)	17.15(5.20)	33.08(9.22)	39.15(5.22)	3.40(7.14)	31.34(7.17)	10.39(1.62)
	p-value	.0268*	> .0001***	.0933	.0005***	.0035**	.0022**	.0008***	> .0001***	0.3340	> .0001***	.0005***
	AP	37	38	39	40	41	42	43	44	45	46	47
Low Semantic Relatedness	CSI(SE)	3.17(4.91)	10.79(3.08)	8.61(4.91)	9.03(3.30)	20.39(6.96)	-5.11(8.37)	-3.59(6.55)	-12.39(7.61)	5.96(5.58)	16.77(6.09)	3.29(3.12)
	p-value	.2766	.0004***	.0478*	.0221*	.0017**	.7371	.6647	.9765	.1405	.0025**	.0867
No Repeated Radicals	AP	60	61	62	63	64	65	66	67	68	69	70
Same Pronunciation	CSI(SE)	2.91(4.16)	6.23(2.00)	3.06(4.09)	9.13(4.18)	-11.69(6.53)	-6.24(4.55)	11.49(5.81)	-11.49(5.27)	35.73(3.95)	-1.87(4.67)	-4.84(2.36)
	p-value	.2472	.0122*	.2286	.0036**	.9664	.8837	.0817	.9824	>.0001***	.6587	.9847
Repeated Phonetic Radicals	AP	23	24	25	26	27	28	29	30	31	32	33
Same Pronunciation	CSI(SE)	9.24(7.19)	9.77(4.08)	7.60(5.41)	24.63(3.78)	9.15(9.55)	9.96(5.67)	15.27(10.43)	15.27(6.71)	43.29(5.32)	10.11(6.62)	5.44(2.65)
	p-value	.0710	.0261*	.0955	> .0001***	.1523	.0491*	.0895	.0140*	> .0001***	.0567	.0289*
	AP	29	30	31	32	33	34	35	36	37	38	39
Different Pronunciation	CSI(SE)	3.14(3.82)	5.18(3.84)	1.07(4.26)	0.70(6.43)	5.79(8.36)	-8.32(6.44)	23.51(7.33)	-9.38(7.08)	-0.90(7.13)	5.40(7.20)	2.32(4.31)
	p-value	.2979	.0892	.4634	.4279	.2317	.8987	.0089**	.8885	.5659	.2226	.2163
Binding Words	AP	11	12	13	14	15	16	17	18	19	20	21
Related Pronunciation	CSI(SE)	25.81(5.19)	25.89(1.98)	12.87(5.17)	3.06(4.99)	16.47(10.18)	34.34(2.50)	50.14(6.03)	40.14(4.61)	16.36(7.41)	34.06(6.52)	7.18(2.10)
	p-value	> .0001***	> .0001***	.0083**	.2778	.0282*	> .0001***	> .0001***	> .0001***	.0104*	> .0001***	.0046**
	AP	28	29	30	31	32	33	34	35	36	37	38
Unrelated Pronunciation	CSI(SE)	18.14(8.19)	25.70(2.52)	17.21(5.95)	13.31(6.88)	33.86(9.48)	20.00(12.42)	38.58(11.27)	49.87(5.72)	-1.85(10.44)	39.35(4.70)	6.03(2.79)
	p-value	.0176*	>.0001***	.0201*	.0336*	.0007***	.0052**	.0009***	>.0001***	.5800	> .0001***	.0901

Note. AP = Available Pairs; CSI = Color Similarity Index; T-T = Transparent – Transparent ; T-O = Transparent – Opaque
*Monte-Carlo $p < .05$. ** Monte-Carlo $p < .01$. *** Monte-Carlo $p < .001$.

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Appendix 2. Character Material List

Set 1.

Semantically related characters without radical repetition

卒	兵	餅	糧
劍	刀	垃	廢
扔	丟	港	船
面	臉	匠	雕
優	好	晒	陽
畏	怕		
乏	少		
郎	男		
持	拿		
按	壓		
憨	笨		
暑	熱		
禪	佛		
噸	重		
磅	重		
棉	軟		
稅	錢		
枕	睡		
燈	亮		
劣	差		
劈	砍		
殃	禍		
堂	室		
叩	敲		
逛	走		
頂	上		
陡	斜		
宜	好		
最	極		
組	群		
群	黨		
季	年		
屑	粉		
折	彎		

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Appendix 2. Character Material List (continued)

Set 2 and Set 3.

Characters with the same semantic radicals and with transparent (column 1 and 2) or opaque (column 3) semantic relatedness

袖	袍	裕
稅	租	秘
唸	喊	唯
皓	皎	的
錫	鋼	錄
脂	胖	脆
根	枝	格
軸	輪	軟
粒	粉	粗
河	泊	法
狼	狸	猜
姊	姑	妨
船	航	般
語	話	諸
醉	醇	酷
飼	飽	飾
貓	豹	貌
碑	磚	確
綿	綢	給
騁	騎	駭

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Appendix 2. Character Material List (continued)

Set 4.

Characters with the same pronunciation but without repeated radicals

兵	冰	就	救
葡	僕	距	鋸
溥	埔	騎	齊
懵	蜢	鞦	邱
閩	敏	前	錢
法	髮	卻	確
扉	妃	斜	諧
匐	服	枝	織
地	蒂	戰	站
噸	沌	柱	佇
蜓	停	綢	躊
檸	凝	唱	悵
郎	狼	城	程
利	粒	施	濕
狸	罹	室	是
冽	劣	使	始
糧	涼	上	尚
路	錄	暑	鼠
高	糕	睡	稅
耿	梗	最	醉
姑	孤	粹	脆
鍋	郭	窈	咬
規	瑰	油	魷
蚣	宮	硯	宴
鏗	坑	佯	陽
河	闔	畏	偽
耗	皓	萎	娓
弧	蝴	彎	蜿
喚	宦	喻	裕
環	桓		
羈	磯		
雞	跡		
借	屆		
膠	礁		

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Appendix 2. Character Material List (continued)

Set 5.

Characters with the same phonetic radicals and with the same pronunciation

妨	坊	格	骼
陶	萄	浦	埔
喚	煥	惆	稠
檸	嚀	崎	騎
檬	朦	混	餛
柱	蛀	脹	帳
玲	羚	唯	惟
秧	殃	驅	軀
瓏	朧	棉	綿
杭	航	線	腺
枝	肢	怕	帕
路	賂	譯	繹
駱	絡	碌	錄

Set 6.

Characters with the same phonetic radicals but with different pronunciation

凍	陳	借	措
蜻	猜	踢	賜
豹	酌	推	准
吋	肘	唾	睡
妃	杞	喝	羯
坑	航	暖	媛
狄	耿	瑰	醜
站	貼	綿	錦
殆	冶	地	她
粒	垃	砍	飲
路	格	投	般
賂	骼	伯	怕
給	洽	酷	皓
蜈	娛	煩	碩
凋	稠	凝	礙

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Appendix 2. Character Material List (continued)

Set 7.

Binding words without repeated phonemes

婀	娜
覬	覦
賄	賂
葡	萄
芙	蓉
蟋	蟀
蝴	蝶
蚱	蜢
瑪	瑙
琥	珀
蜈	蚣
枸	杞

Set 8.

Binding words with repeated phonemes

惆	悵	傀	儡
琵	琶	齷	齪
枇	杷	蹣	跚
崎	嶇	窈	窕
坎	坷	垃	圾
尷	尬	玲	瓏
鞦	韆		
躊	躇		
躑	躅		
檸	檬		
徘	徊		
徜	徉		
玫	瑰		
橄	欖		
餛	飩		
憧	憬		
懵	懂		
嘮	叨		
蜻	蜓		
蹉	跎		
妊	娠		
匍	匐		

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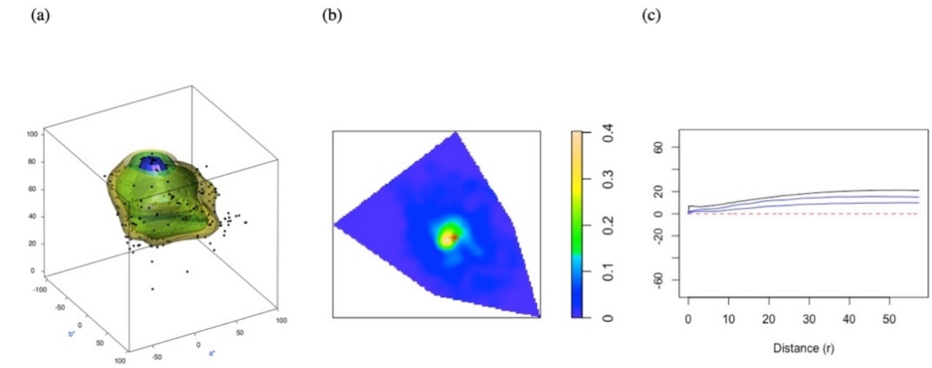
Appendix 3. Density Plot and L-function of Each Synesthete

(a) Density plots of the synesthetic colors in the CIE L*a*b* color space

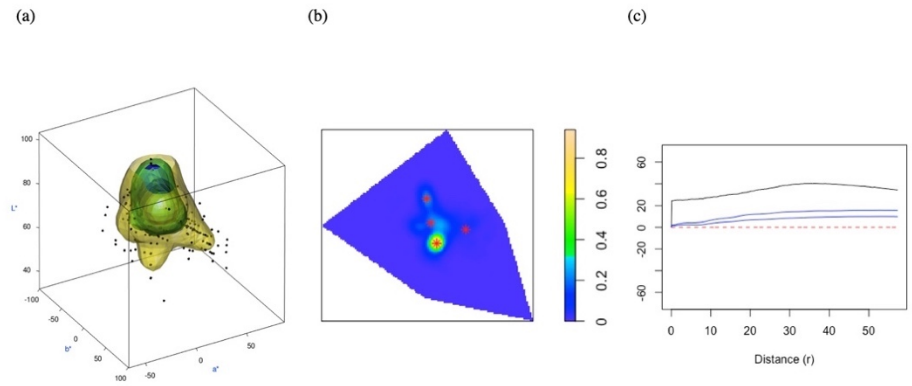
(b) Density plots of the synesthetic colors in the a*b* chromaticity plane

(c) L-functions of the point patterns for chromatic synesthetic colors at a distance r from a given point

YHC



CCD



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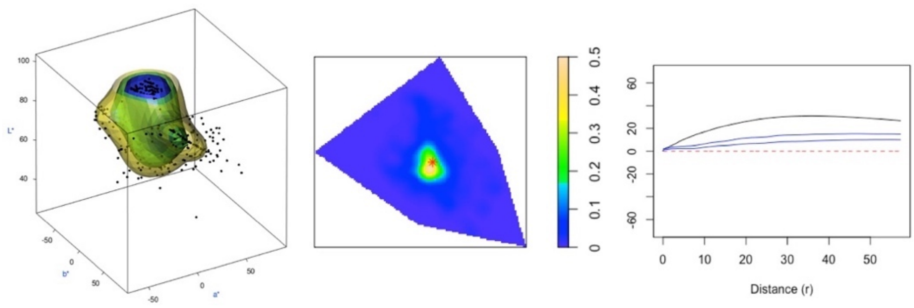
YSL

(a) (b) (c)



YLK

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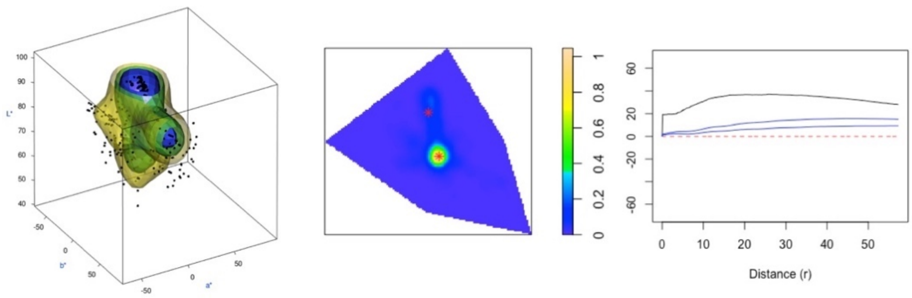

YPW

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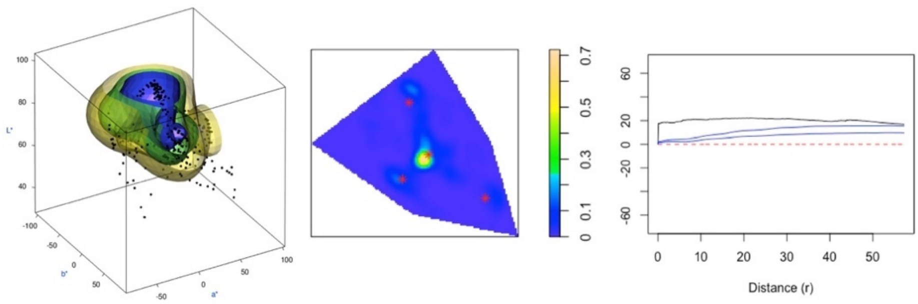
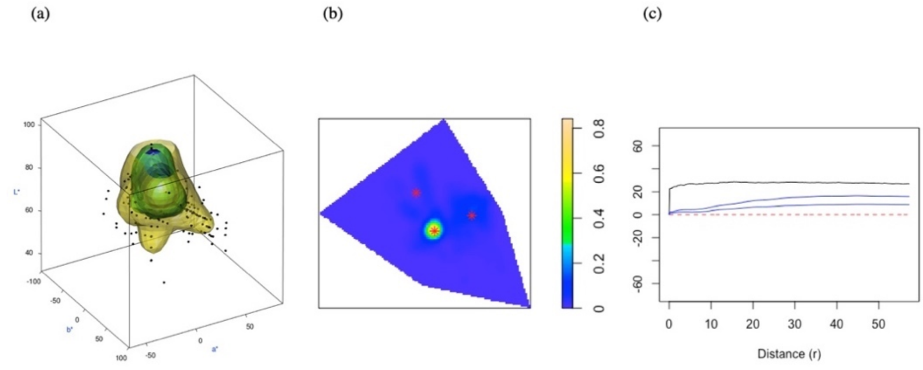
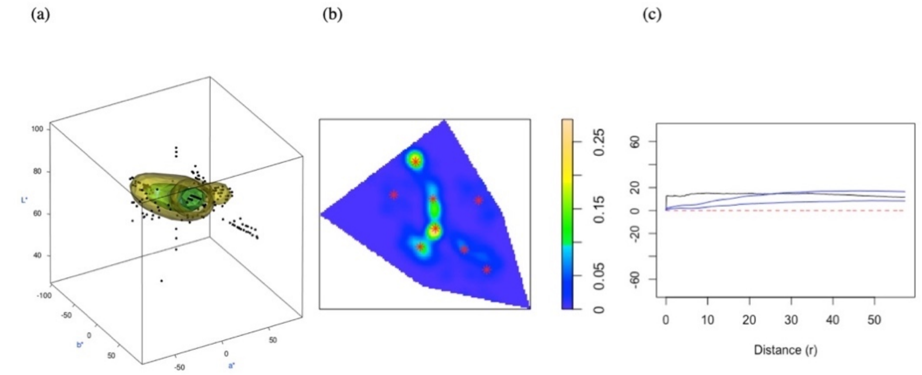


doi:10.6342/NTU201903697

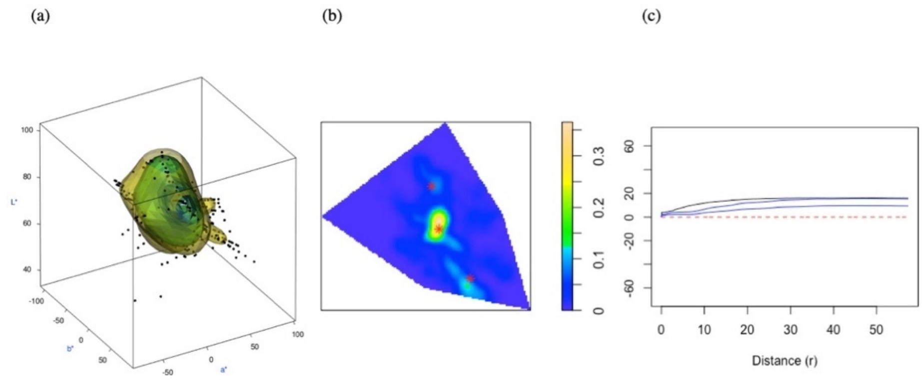
CLC



HLC



MCH



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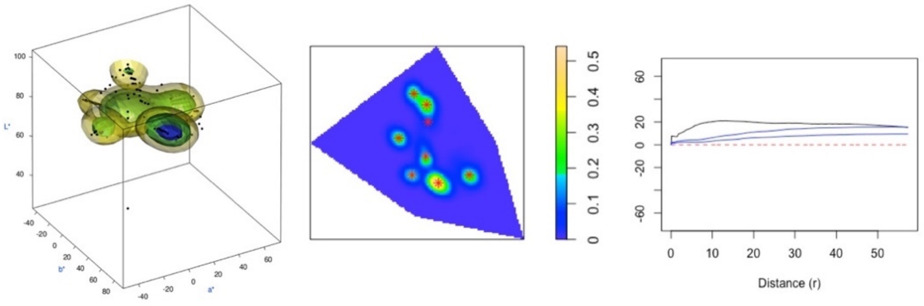
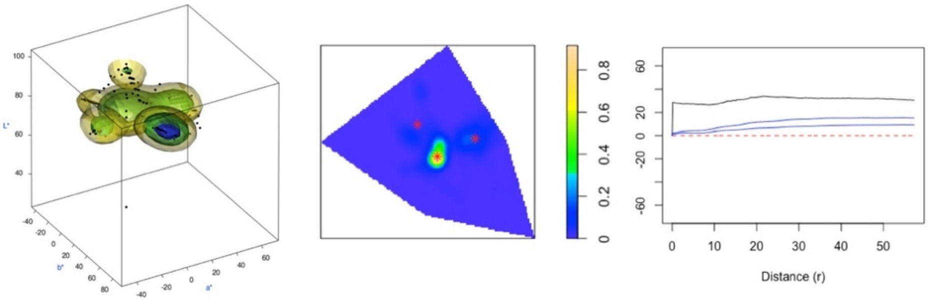
YST

(a) (b) (c)



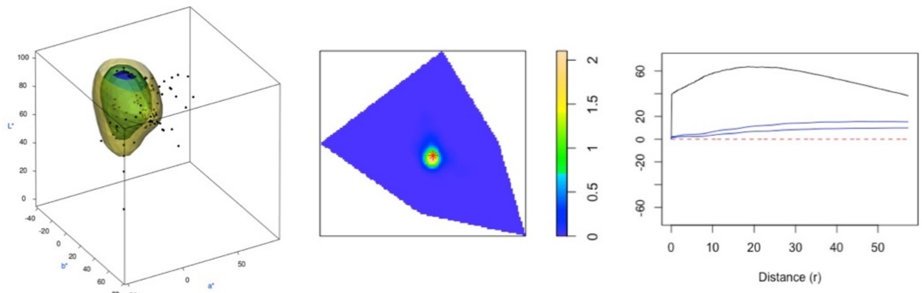
TCL

(a) (b) (c)



YTL

(a) (b) (c)



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