

An investigation of color preference using behavioral study and electroencephalogram analysis

Songyang Liao

Graduate School of Human Sciences

Kanagawa University

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論文要旨

I. 問題提起と研究目的

色の好みについては19世紀から研究されてきた。人々は日常生活の中で、色の評価をし、特定の色を選好している。従来、色の好みの研究は異なる文化や地域、性別、年齢、性格などに焦点を当て行なわれていたが、色の好みがどのように生じるかについてはほとんど知られていない。近年、いくつかの研究が色の好みの原因を突き止めた。しかし、結論については依然として議論の余地が残されている。

Hurlbert & Ling (2007) は色の選好が cone contrast (コーン・コントラスト) の低次の視覚情報に基づいて、網膜上の L, M, S 錐体間で応答の比率、特に[黄青]コントラストで色の選好を決めていることを提案した。人は男女問わず青みの色が好み、女性は男性より赤み色を好むことが報告され、色の選好は人間の進化過程で視覚神経に組み込まれていると結論をつけた。

一方、Color emotion model (Ou, Lou, Woodcock, & Wright, 2004, 2004a, 2004b) と Ecological Valence Theory (Palmer & Schloss, 2010) では色の選好が記憶と感情処理のより高次の認知段階に寄与していることとされた。Color emotion model では色を見るとき生じた感情により色の選好が変化し、人はより清潔な、平然たる、明るい印象をつけた色を好み、反対に、より汚い、緊張な、重い色が嫌われることを説明している。Ecological Valence Theory は色に関連付けられた物体の好き嫌いで色の好みを決める。人が一般的に青を好むのは青い空と澄んだ水などに積極的な反応をするのに対して、濃い黄色を嫌うのは糞便や嘔吐物に消極的な反応をするためであると説明している。この三つの研究では色の好みの理由を説明し、予測モデルを開発した。しかし、次の二つの問題において意見が一致していない。

- 1) 色の選好はどのように生じるか？
- 2) 好む色を評価するとき、人の脳の中でどのようなプロセスを行なわれているか：低次の感覚情報で決まるのか、または高次の認知情報に依存するのか？または両方の情報を統合して決定するのか？

色の選好の原因とその機序を理解することは人の知覚認知と意思決定の繋がりを理解するのに役立つ。一方で、解明した機序に基づいて色選好の予測モデルが開発できれば産業応用にも貢献が期待される。これまでの研究では色の選好性の機序を多くは行動研究によって検証されてきたが、本論文では行動研究とともに、大脳皮質における神経活動の解析を行なうことで、より客観的応答を基にした色選好性の機序についての解明を行うことを目的にしている。

本論文の構成は以下に示す通りである。第1章は先行研究を概観し、本研究での研究課題とその目的を述べている。第2章（研究1）では色の好みの原因を推測するために行動研究が行われた。色の好みは高次の認知処理からの情報（記憶または感情）による単純接触効果（Mere Exposure Effect）に基づいて誘発されるという仮説を検証し、この仮説に基づいて色の選好を予測してみた。第3章（研究2）では色を評価するときの脳の活動を示すために脳波（EEG）の計測を行なった。その結果、選好性に依存した脳活動のパターンを確認した。第4章では前章までの結果を受けて総合的に考察を行った。

II. 研究1（実験1・実験2）

単純接触効果は刺激を繰り返し接することで好意度を高めるという効果である（Zajonc, 1968）。この効果は顔、図形、言葉などいろんな刺激に対して起こる。しかも高次の認知処理（記憶と感情）に頼る。研究1の目的は色の好みが生じるという仮説を検証することである。色の好みと物の記憶色との関係を調べて色の選好の予測モデルを提案する。実験1ではよく見られる物体の記憶色を見つけるため、五種類の果物と野菜を用意した。物体の色度をD65の標準光源下で測定してCIELAB空間で同じ間隔で刺激のバリエーションを作成した。観察者は各刺激とその物体の記憶色との類似性を評価した後、ガウス関数で物体の記憶色を求めた。記憶色は標準光源下で測定された色より高い彩度を持つ傾向があることが明らかになった。実験2では、実験1で得られた記憶色を中心に色空間上において等間隔で新しい刺激を作成して、実験1とは別の観察者が色について自分の好みを評価した。実験の結果、色の好みと記憶色の間には2種類の関係が明らかとなった：1）赤から緑までの色については、赤-緑信号の軸で非線形回帰が見られて、観察者は記憶色に近い色を好むことを示唆した；2）青と紫の色については、黄-青信号の軸で線形回帰があつて、観察者はより青く見える色を好むことを示した。さらに、重回帰モデルを適用すると、色選好データの63%を説明できた。

研究1では赤、黄、および緑の色に対して単純接触効果が見られたが、紫と青ではその効果はなかった。この結果からは三つの推測が得られた：1）Mollon（1989）は霊長類が赤、黄、緑色の果物を頼っていて、赤-緑信号は果実を森の中で検出し、熟度を判断するので重要な役割を果たしていると報告している。本実験の結果では、赤-緑信号は色の検出だけではなく、好みにも大きい寄与していること、また、果物の記憶色に近いほど好まれていて、記憶色から離れるほど好まれないため、人は最も食物らしい色を好むと考えられる。一方で、青や紫の果実は[鳥の果実]（Janson, 1983）と指摘されており、食物の色と同じパターンに従う判断とは異なることが示されたことから、これらがMollon（1989）によって支持される。2）食物に関連する赤か

ら緑の色の選好だけ単純接触効果が寄与しているため、長期にわたる進化の過程で発達してきたことが示唆される。3) 色の評価機序は低次の色情報（赤-緑信号）と高次の認知情報（単純接触効果）を統合する過程であることが示唆される。

III. 研究 2（実験 3）

シータ波は主に海馬で発生し、脳全体に広く分布する情動、記憶に関する高次認知機能と言われている。これまでの研究は顔、画像、日常消費品などについての選好を評価するときの脳波のパターンが解明されており、シータ波は物の選好についての脳活動として強く関連をしていることが報告されている。研究 2 では EEG を使って色を評価中の脳活動、特にシータ波を測定して、次の二つの問題を解明することを目的とした：1) 色選好の評価は情動反応か？2) 好む色と好まない色を見るとときには積極的および消極的な感情が起こされるのか？

実験は薄暗い部屋で行なわれ、観察者はモニター上で 32 色を評価し、その際の脳波が同時に測定された。各観察者に最も高い評価された 10 色は好む色、最も低い評価された 10 色は好まれない色とした。刺激呈示後 200 ～ 500 ミリ秒の間のシータ波 (4-8 Hz) を時間周波数解析して比較した結果、好む色を見ると左前頭部が活性化され、好まない色を見ると左後頭部が活性化されることが観察された。さらに、色の好み（好む色と好まない色）と電極の位置（左前頭部、右前頭部、左後部、右後部）の二元配置分散分析を行った結果、二つの要因および相互作用に有意差が見られた。好む色を見たとき左前頭のシータパワーが右前頭と後頭部より大きいことから、この前頭部のシータ波の非対称性は積極的感情の応答に関連していることが推察される。また、好まない色を見たとき左後頭のシータパワーが他の部分より大きいことから、これは記憶検索に関する活動と考えられる。

この EEG 実験では好む色と好まない色を評価する際に異なる神経活動が得られることを示した。好む色を評価するのは情動反応と見られ、顔、画像選好の脳波実験と同様なパターンを観察した。一方で、好まない色の評価は記憶検索に関連している可能性があることも推察される。Yeh ら (2015) は、観察者が以前の経験を検索して比較する際にそれらの評価を行う必要があると提案した。観察者は色に積極的感情が起こさない場合、特定の経験の記憶で色の選好に決めると考えられる。

IV. 総合的考察

本論文では行動研究と脳波研究の両方によって色の選好性の機序を客観的に明らかにした。この研究の結果から三つの結論を導き出した。

一つ目、色彩選好は先行研究の提案した単なるの低次の感覚情報、または、高次の認知情報に依存するのではなく、初期の視覚情報と高次の認知情報に統合より決定されている。特に単純接触効果は赤-緑信号に影響しており、食物の記憶色に近い色が好まれる。黄-青信号には単純接触効果が影響なく、より青い色ほど好まれる。

二つ目、単純接触効果は色の好む原因を部分的に解釈できる。EEG 実験の結果、好む色が積極的感情に関連していることが解った。そして単純接触効果は一部の色（赤から緑まで）についての積極的感情を説明できる。色が記憶色に近いほど、単純接触効果による積極的感情が強くなり、より好まれる。

さらに、好まない色の評価は好む色とは異なる神経活動に頼ることが明らかになった。Ecological Valence theory と Color emotion model では、色の好き嫌いは積極的と消極的感情両方による評価されるとされている。一方、本研究の結果では、好まない色は消極的感情とは関係なく、積極的感情の減少には関連していることが示された。色に対して積極的感情が生起されない場合には、人は情動反応としての脳活動は観察されなかった。これは、好まない色の評価には記憶検索過程のみが関与しているためであると考えられる。

Hurlbert と Ling (2007) および Palmer と Schloss (2010) の研究では、色の選好は進化過程で発達してきたと提案している。Hurlbert と Ling (2007) は狩猟採集説 (Hunter-gatherer theory) を強調し、女性が熟した果実を集める役割を担っていたため、男性より赤みを好むことになってきた。また、Palmer と Schloss (2010) が述べているように、人が生存率と繁殖力を高めるために、[見栄えのよい]色を好み、[見栄えの悪い]色を嫌うことを述べている。一方、本研究では性差などについては議論していないが、実験結果は男女関わらず、最も適切な食物の色を好むことが明らかとなった。

本研究は赤-緑信号に依存する色彩選好の機序を解明したが、黄-青信号による機序はまだ解けていない。今後、[黄青]コントラスト、特に S 錐体からの寄与に関するより詳細な研究が必要と考えている。

Abstract

As an everyday visual experience, it is known that people tend to prefer specific colors over others. Conventionally, color preference studies focused on the differences in culture, gender, age, and personality. Recently, studies have explored its causes and the underlying mechanism. The biological components theory focuses on the contribution of the cone-opponent system of color vision from the early sensory stage. Color-emotion model and ecological valance theory emphasized the importance of the higher-level cognitive stage of memory and affective processing. However, the conclusion is still under debate. This thesis conducted behavioral and electroencephalogram (EEG) studies and sought to address two questions: (1) how color preference arises, and (2) the mechanism underlying color appreciation. The behavioral study tested the hypothesis that color preference is induced by the mere exposure effect. The results showed the integration of the mere exposure effect and the red-green signal from the low-level color vision system. For those “food colors” (red, yellow, and green), the closer the color was to the memory color according to the red-green signal, the more it was preferred and vice verses. Since the red-green signal is crucial in detecting ripe fruits and forming color preference, we hypothesized that color preference was adaptive and developed during the evolution. The EEG study identified the type of brain activity that occurs during color appreciation. Color appreciation is high-level cognitive processing in which assessing preferred colors was related to affective processing while assessing non-preferred colors relied on memory-retrieving processing. We concluded that the mere exposure effect could partially explain color preference and that color appreciation is determined by integrating early-stage color information and higher-level cognitive information. The current study clarified the mechanism of color preference depending on the red-green signal. Further research on the yellow-blue signal, especially the contribution from the S cone, is needed.

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Chapter 1 General Introduction

1.1 Overview

Color preference has been studied since the 19th century (for a review, see Taylor, 2011). People experience color preference daily, liking certain colors over others. Conventional color preference studies have compared cultures and geographical locations (Adams & Osgood, 1973; Saito, 1996), genders (Bonnardel et al., 2018; Ellis & Ficek, 2001; Fortmann-Roe, 2013; Franklin et al., 2010), ages (Adams, 1987; Beke et al., 2008; Taylor et al., 2013), personalities (Bakker et al., 2015; Bonnardel et al., 2018), and contexts (Hanss et al., 2012; Liao et al., 2018; Shieh & Yeh, 2015; Wei et al., 2015). Most studies have focused on how color preferences differ in hues, saturations, and values; however, little is known regarding how color preferences arise. Although several studies have examined the cause of color preference (Hurlbert & Ling, 2007; Ou et al., 2004a, 2004b, 2004c; Palmer & Schloss, 2010), no consensus has been reached. Therefore, this thesis conducted behavioral and electroencephalographic analysis to provide new insight into the cause of color preference and reveal the schematic mechanism underlying color appreciation.

1.2 Current Theories on Color Preference

Several existing studies investigated the cause of color preference and developed color preference prediction models to explain variance in their data. However, this issue remains a matter of intense debate.

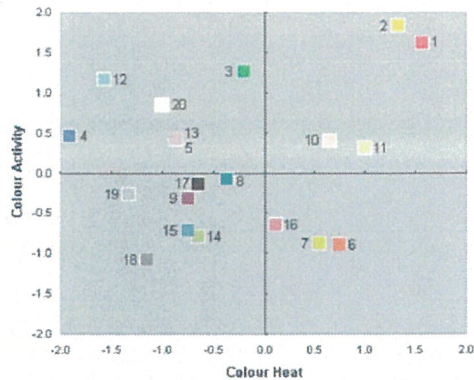
1.2.1 Color-Emotion Association

Ou et al. (2004a, 2004b, 2004c) believed that color preference was based on the emotions that arise when viewing colors. In a paired comparison experiment, participants (31 Chinese and British students) selected a word from a color-emotion word pair that was associated with the stimuli (20 colors from the natural color system). The ten color-emotion word pairs were created based on previous studies: active-passive, fresh-stale, clean-dirty, modern-classical, warm-cool, hard-soft, masculine-feminine, heavy-light, tense-relaxed, and like-dislike.

The first model was created based on three color-emotion associations: clean-dirty, tense-relaxed, and heavy-light. Participants preferred colors that were cleaner, more relaxed, and lighter. They determined color preference by giving weights to each variable in a multiple regression model, which explained 66% of the data variance.

The second model was based on three color-emotion factors. Ou et al. extracted three factors using factor analysis: color activity (active-passive, fresh-stale, clean-dirty, and modern-classical), color heat (warm-cool), and color weight (hard-soft, masculine-feminine, and heavy-light), which accounted for 79% and 90% of the variance for British and Chinese data, respectively. They found that color weight and heat were negatively correlated with preference, whereas color activity and preference had a positive correlation. This means that the participants liked colors that were lighter, more relaxed, and more active (Figure 1.1). Ou et al. further determined these factors using the color location in *CIELAB* color space, which is a perceptually uniform space based on the opponent color model of human vision, where L^* was perceptual lightness, a^* indicated red and green opponent pairs, and b^* indicated yellow and blue opponent pairs, as well as chroma and hue angle. A color preference prediction model was created by assigning weight to each factor. This model explained 67% of the variance in their color preference data.

(A)



(B)

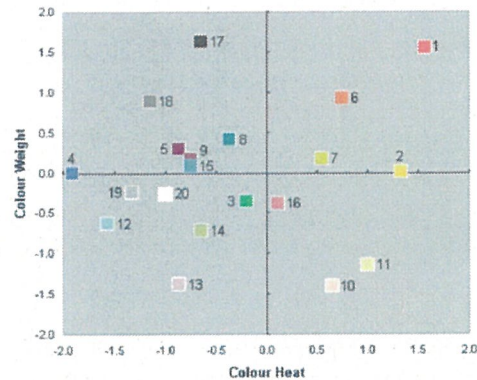


Figure 1.1. A plot of 20 colors along (A) color activity and heat, indicating that participants preferred more active and cooler colors located in the top left corner, and (B) color weight and heat, indicating that participants preferred lighter and cooler colors located in the bottom left corner. Taken from Ou et al. (2004a).

1.2.2 Biological Adaptation

Hurlbert and Ling (2007) developed an idea based on the two cardinal dimensions of opponent cone-contrast: a red-green color signal derived by dividing the output of the L by M cones ($L-M$) and a blue-yellow color signal derived by dividing the output of the luminance signal ($L+M$) by the output of the S cones ($S-[L+M]$). L, M, and S refer to three cone classes with different likelihoods of absorbing the light of short, middle, and long wavelengths, respectively. They collected hue preferences from British and Chinese cultures. They conducted three experiments and asked the participants to pair-wise compare colors (8 hues) with the same lightness and different saturation or vice versa. They pooled the proportion of the selected hues and plotted a hue preference curve (Figure 1.2). The curve revealed that women's preference peaked in the reddish-purple region, whereas men preferred colors in the blue-green region.

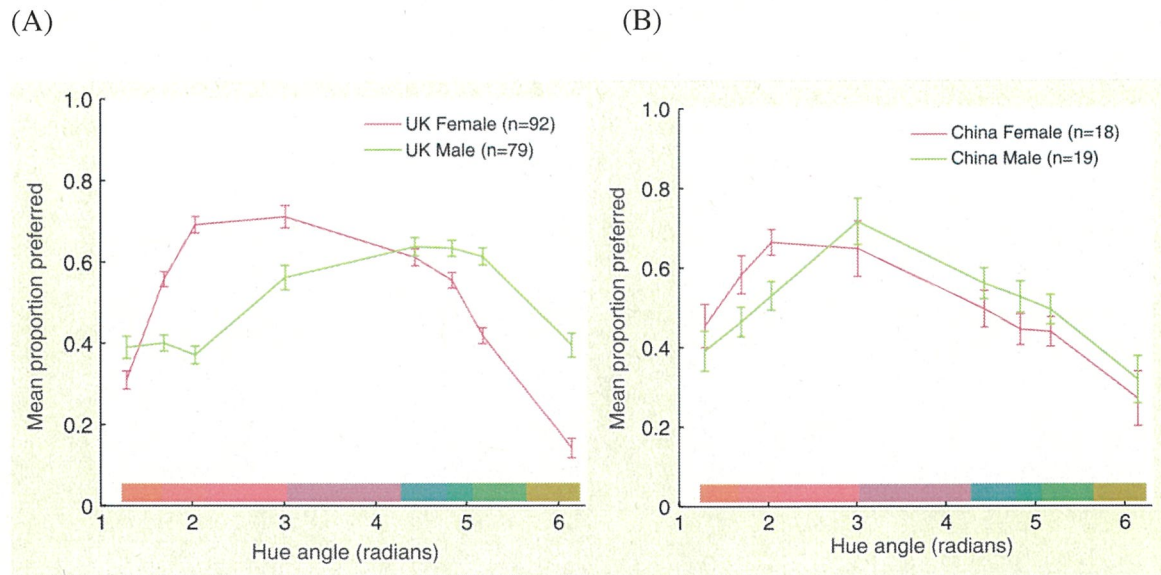


Figure 1.2. Mean hue preference curves for (A) British and (B) Chinese participants. The horizontal axis indicates the tested hues, and the vertical axis is the mean proportion preferred calculated from how many times the hue was selected in the pair-wise comparison. Taken from Hurlbert and Ling (2007).

Hurlbert and Ling (2007) further calculated the LM (red-green) and S (blue-yellow) cone-contrasts components (against the background) and developed a prediction model by assigning weights to each component. This model explained 70% of the variance for their data, in which the blue-yellow contrast component explained 44.5%, and red-green explained 25.5% of the variance for the whole population. All populations preferred blueish color over yellowish, indicated by positive weight assigned to $(S-[M+L])$. This model was updated in a later study (Ling & Hurlbert, 2007) by adding luminance contrast $(L+M+S)$ and color saturation.

Based on these results, Hurlbert and Ling (2007) argued that the general blue preference and gender differences were hard-wired into the visual neuronal system during evolution. And that women's preference for reddish color was due to their traditional roles as "gatherers" (responsible for collecting ripe food in the foliage) and "caregivers" (requiring an

understanding of subtle skin color differences according to emotional and social-sexual signals).

1.2.3 Ecological Valence Theory

Palmer and Schloss (2010) developed the Ecological valence theory (EVT), which suggests that color preference should be adapted from long-term (evolution) and short-term (learning) time scales. From the adaptive perspective, people are attracted by objects whose colors look good and avoid those that look bad for survival and reproductive success. Palmer and his colleagues also conducted a series of studies to prove that color preference can be learned during life experiences and is dynamic. They challenged the color-emotion model proposed by Ou et al. (2004a, 2004b, 2004c), as it could not explain why viewing colors evoked emotion, and the biological components theory (Hurlbert & Ling, 2007), as it could not determine why men prefer violet over women.

The EVT argues that people like certain colors because they like the objects associated with them. People's general color preference for blue is due to positive responses to blue sky and clear water, and their dislike of yellow is due to the negative responses to feces and vomit. Palmer and Schloss's experiment included four tasks. In Experiment 1, participants were asked to rate their preferences for 32 colors from the Berkeley Color Project (BCP). The participants in Experiment 2 shared the objects they could associate with each color. The participants in Experiment 3 provided affective ratings to colors. In Experiment 4, the participants matched objects with colors.

Figure 1.3 (A) depicts the mean color preference, averaged for 48 participants, and (B) represents the average affective valence to the colored objects: weighted affective valence estimate (WAVE). These two sets of data were strongly associated with each other. Take the preference for Saturated Red as an example. Saturated Red was associated with 19 objects, such as blood, cherries, and fire. In the color-object matching phase, blood matched with Saturated Red at 0.45, cherries at 0.50, and fire at 0.44. Then, in the affective rating phase, blood was rated at -27.73, cherries at 44.54, and fire at 0.23. During the calculating phase, the object matches and affective response were multiplied and averaged to obtain the WAVE. This WAVE predictor was proven to explain 80% of the variance for their data taken in the

United States (US). A follow-up study demonstrated that color preference could be predicted better by participants' individual WAVE than other people's WAVE (Schloss et al., 2015).

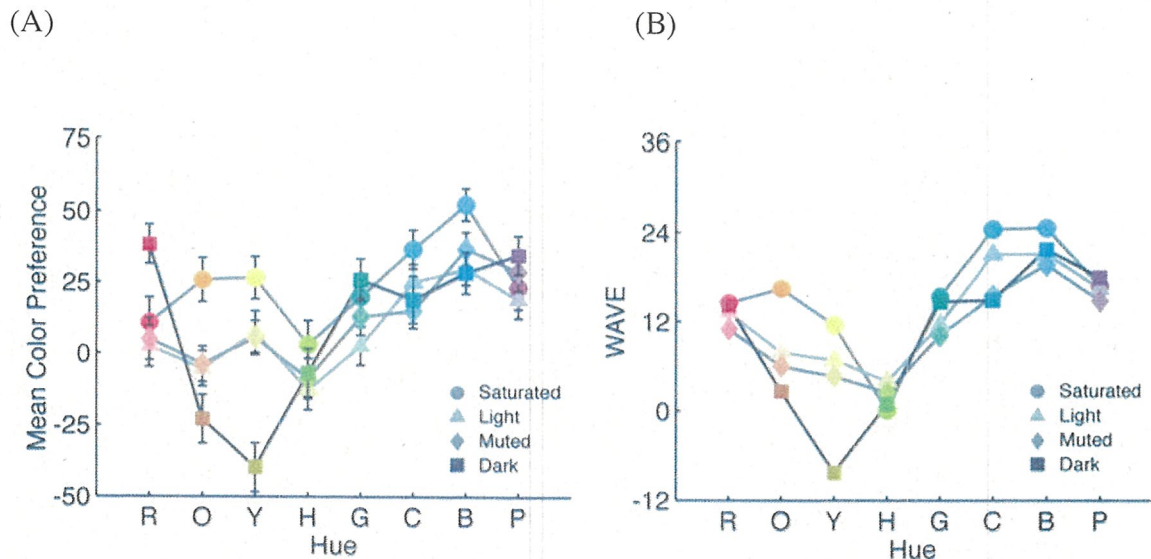


Figure 1.3. (A) Mean color preference of 48 participants; (B) weighted affective valence estimate (WAVE) calculated from the affective response to the colored objects. WAVEs for the 32 colors were strongly correlated with preference. Taken from Palmer and Schloss (2010).

To demonstrate that color preferences develop from lifetime experiences, Schloss et al. (2011) investigated whether students from various universities like their university colors. The results showed that students preferred the colors of their own university more than those of their rivals. Furthermore, the preference ratings were correlated with the school spirit levels. Higher school spirit levels indicated stronger preference for their own university's colors and lower preference for rivals' colors. Yokosawa et al. (2016) compared the color preferences of three cultural groups: Japanese people, Japanese people who live in the US (multicultural), and Americans. The correlation between multicultural and American groups' preference ratings was significantly higher than that of Japanese and American groups, as multicultural groups associate colors with objects from both cultures.

Moreover, color preference is dynamic. Color preferences were shown to change after giving an affective response to the color-associated objects (Strauss et al., 2013). The

preference for red increased after participants assigned valence ratings to positive red pictures, such as roses, apples, and cherries. In addition, preference changed on different occasions, depending on which color-object association was activated. On election day, Republicans preferred Republican red more than Democrats. However, they preferred Republican red equally on non-election days (Schloss & Palmer, 2014). To predict preference change based on occasion, Schloss et al. (2017) suggested adding an activation term to the original WAVE equation. The prediction for color preference in autumn improved, as people liked autumn-related colors, such as dark red, orange, yellow, and chartreuse, more than those in the other three seasons.

1.2.4 The Need for Further Research

The above studies provided hypotheses regarding color preference with prediction models that explained most of the data variance. However, all three studies assumed that the preference toward the most representative colors within each color category represents the preference of all colors in the color spectrum. The EVT tested 32 BCP colors, the color-emotion model tested 20 colors, and the biological components theory only focused on hue differences among eight hues. These abstract colors were selected carefully as representative colors for each color category based on the experimenters' criteria and contained specific semantic meanings, symbolic associations, and abstract concepts. Thus, the results were more likely to suggest the mechanism behind the color preference for particular colors. To investigate the preference for unlimited colors in the color spectrum, we need to develop the stimuli in a more natural way.

Second, the above studies did not agree with each other on the most fundamental question: how color preferences arise. Hence, the process during color preference appraisal was inconsistent. Ou et al. (2004a, 2004b, 2004c) argued that emotions arise from viewing colors. Palmer and Schloss (2010) stated that one must rely on affective responses to colored objects. These two studies suggested that color preference appraisal is a high-level cognitive process involving memory and affective processing. Conversely, Hurlbert and Ling (2007) suggested that color preference is innate and wired into the biological components of color

vision. They argued that after acquiring S, M, and L cones, people prefer specific colors over others; thus, color preference appraisal is rooted in a low-level perception process.

Furthermore, the performance of the models was unstable when experiments were conducted in different countries and with different stimuli. The explained variance of WAVE varied even with the same stimuli. It explained 80% of the variance of data for American participants (Palmer & Schloss, 2010), 66% for British participants (Taylor & Franklin, 2012), 36% for Japanese participants (Yokosawa et al., 2016), and 23% for Himba participants (Taylor et al., 2013). The biological components theory failed to predict color preference among Himba participants. The models' prediction worsened when the tested stimuli changed or increased. Palmer and Schloss (2010) retested the biological components theory and color-emotion model with 32 BCP colors. The biological components theory could only predict 37% of the preference, and the color-emotion model predicted 55%.

Moreover, these three hypotheses did not fully explain the cause of color preference, with unexplained variance remaining in each model, which indicates that there may be alternative explanations.

1.2.5 The Importance of Understanding Color Appreciation Mechanisms

People make color preference decisions daily for a better quality of life. This should be based on specific mechanisms that apply to all human beings. In industry, color preference helps promote products (Hanss et al., 2012; Liao et al., 2018; Schloss et al., 2013) and deliver communication messages to the target audiences in designs (Bartneck & Clark, 2015; Lichtlé, 2007; O'Connor, 2015). Previous studies have focused on the behavior-level explanation of color preference and investigated color preferences among different groups, on different occasions, and at different ages. With the development of cognitive neuroscience, a more precise neural activity could be proposed for behavioral explanation. Understanding the cause and mechanisms of color preference will contribute to understanding the relationship between perception, cognition, and decision-making. Furthermore, developing a color preference prediction model based on underlying mechanisms could improve industry efficiency.

1.3 Mechanisms Underlying Color Appreciation

In perceptual decision-making tasks, when participants are required to distinguish a specific object from others, two general stages are involved: early sensory processing and accumulation of evidence to a decision threshold (Philiastides et al., 2006; Philiastides & Sajda, 2007). For instance, in a face-house discrimination task (Heekeren et al., 2004), the higher-level cortical region (dorsolateral prefrontal cortex) forms the decision based on the outputs from selective lower-level regions (ventral temporal cortex) that respond more to faces than houses.

Preferential and perceptual tasks share the commonality that uncertain information must be processed before decision-making. Participants need objective information to make decisions as accurately as required for perceptual tasks. However, they must rely on the personal subjective goals and a higher cognitive level to form preferential decisions (Dutilh & Rieskamp, 2016). Therefore, we constructed a general schematic model describes the mechanisms of color appreciation (Figure 1.4). The information from early sensory processing (color information) integrates with high-level cognitive processing (memory, affect, etc.) to make a preferential decision. At the beginning of the early sensory processing of color information, there are three cone types in the retina (L, M, and S), which are sensitive to long, medium, and short wavelengths of light, respectively. The cones compare the ratio of activity using opponent coding. The output of L cones divided by that of M cones derives the red-green color signal, and the output of the luminance signal (sum of L and M cones) divided by that of S cones derives the yellow-blue signal. This visual signal is conveyed to the cortex, the primary visual cortex V1, and the critical area V4 in achieving the normal perception of color. After the colors are successfully perceived, the color information is sent to the cognitive integration system and integrated with the information from higher-level processing, such as memory and affect. Finally, the decision-making system decides the color preference.

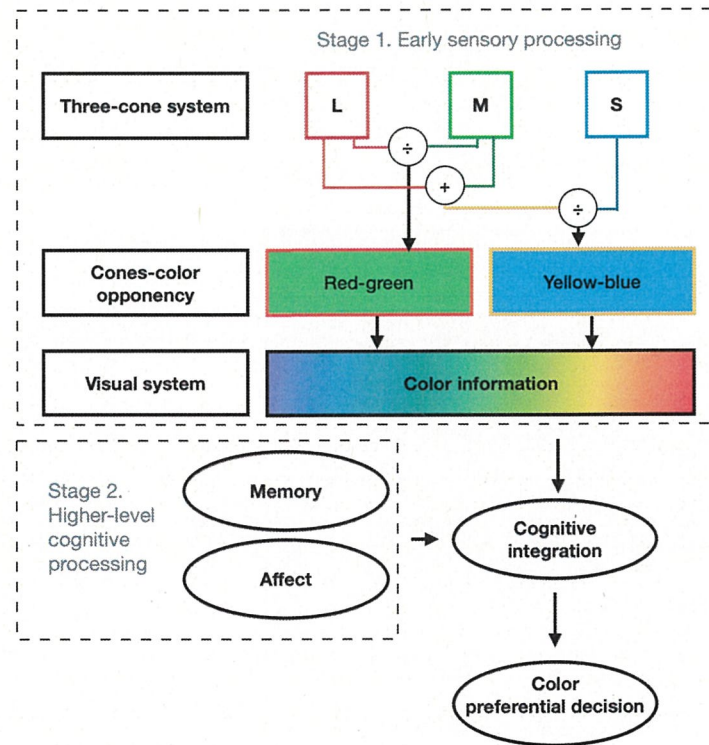


Figure 1.4. Diagram depicting the suspected schematic mechanism of color appreciation

The aforementioned three studies emphasized the contribution of different stages during the process. Hurlbert and Ling (2007) focused on the early sensory processing stage in cone opponent, especially the yellow-blue signal, which accounts for most of the variance in their color preference data; however, higher-level cognitive processing was not discussed. Conversely, the color-emotion theory (Ou, et al., 2004a, 2004b, 2004c) focuses on emotions evoked by colors. Furthermore, the EVT (Palmer & Schloss, 2010) addresses the affect of objects that one can associate with colors. The latter two theories emphasize higher-level cognitive processing. This thesis investigated whether the mechanisms explained by these three theories are valid and whether color appreciation is associated with early sensory cognitive processing, high-level cognitive processing, or an integration of both.

1.4 Mere Exposure Effect and Preference

Mere exposure is a general theory that explains how people form preferences toward specific stimuli. It suggests that preferences increase with repeated stimuli exposure (for a review, see Bornstein, 1989; Zajonc, 1968). Zajonc (1968) described that attitude toward the stimulus would be enhanced by making “the given stimulus accessible to the individual’s perception” (p. 1). In his study, the subjects from the US were shown “nonsense words” (Chinese-like characters) and asked to guess their meaning on a good-bad scale. There was a positive correlation between affective connotation and repetition of characters. This phenomenon was proven to be reliable with different types of stimuli, such as colors (Hupbach et al., 2006), faces (Harmon-Jones & Allen, 2001; Liao et al., 2011; Park et al., 2010), geometric shapes and patterns (Lee, 2001; Seamon et al., 1995), brand names (Hansen & Wänke, 2009), music (Madison & Schiölde, 2017; Peretz et al., 1998), and food (Pliner, 1982).

1.4.1 Positive Affect Induced by Mere Exposure

Studies have attempted to explain the positive affect of mere exposure; however, they could not reach an agreement. Bornstein (1989) explained the mere exposure effect from the evolutionary aspect using a modified two-factor model (Berlyne, 1970). Preference for familiar rather than novel objects is adaptive. When confronted with selection, if the object is familiar, one can rely on previous experiences with that object. In contrast, an unfamiliar object means potential risk. Seeking safety over the unknown is an evolutionary advantage. Garcia-Marques and Mackie (2000) stated that repetition produces a feeling of familiarity, which is positive in valence. In their study, repeated messages produced more positive moods among the participants than novel messages. They suggested that familiar information processing matches the target stimulus with stored representations, creating a top-down retrieval strategy that is effortless and non-analytic. Unfamiliar situations require more effort and bottom-up computational work. Thus, familiarity is associated with the ease and fluency of stimulus processing. Winkielman and Cacioppo (2001) claimed that the feeling of familiarity is not directly related to a positive affect, but all factors contributing to processing facilitation, including repetition, priming, prototypicality, and presentation condition (duration, contrast, clarity). In a facial electromyographic (EMG) experiment, the activity of the zygomaticus

region muscle (cheek muscle) increases during positive affective states and decreases during the negative affective state. Their study showed more zygomatic muscle activity among the participants by increasing the presentation time without repetition.

Moreover, studies have shown that mere exposure could reduce the negative affect. When facing a novel stimulus, approach and avoidance responses could occur. If the consequences are benign, avoidance is eliminated (Zajonc, 2001). Consequently, the negative affect is reduced. Lee (2001) suggested that mere exposure relies on “uncertainty reduction” (p. 1255). In addition to prior exposure, subjective familiarity and confidence level were considered. The results showed that observers preferred the stimuli they thought they were exposed to more than those they believed were novel, regardless of whether the stimuli had been shown before. Confidence level was positively correlated with preference, indicated that the participants liked the stimuli more if they felt more confident during the judgment.

1.4.2 Mere Exposure and Memory

The mere exposure effect is based on implicit rather than explicit memory. Implicit memory is previously acquired information that could be retrieved unconsciously, such as riding a bike or navigating a familiar area. In contrast, explicit memory requires conscious recollection, such as experienced events or friends’ birthdays. Seamon et al. (1995) tested this idea with three-dimensional blocks. They randomly showed blocks to different groups of participants for 4 ms or 6 ms, a total of 120 times in the study session. In the main experiment, participants examined whether they had seen the block before (recognition test, which reflects explicit memory) and whether they liked the block (mere exposure effect test). Their results showed that recognition did not exceed the chance level, but participants preferred the old blocks significantly greater than the chance level. This indicated that the mere exposure effect was independent of the recognition task, demonstrating implicit memory. A functional magnetic resonance imaging (fMRI) study had a similar conclusion, revealing that the preference induced by mere exposure and explicit recognition involved the activation of different parts of the brain (Elliott & Dolan, 1998). Participants were shown Japanese ideograms (which were not identifiable to the participants) in the pilot study before the scan (50 ms, 10 times for each ideogram). The left frontopolar cortex and parietal areas

were activated during the memory judgment, whereas the medial prefrontal and occipital cortices were activated during the preference judgment.

Thus, we can assume that if one acquires the memory of the color of a specific object in their daily life by mere exposure, it is stored in the brain as implicit memory. During color appreciation, the mere-exposure-induced positive affect integrates with the color information to form preferential decisions.

1.5 Neural Correlates of Higher Cognitive Functions

This study investigated the higher-level cognitive processing of affect and memory during color appreciation using EEG. Cognitive neuroscience has related these processes with specific neural mechanisms by which they occur in the brain, especially the activity for theta oscillation. Theta frequency (approximately 4-8 Hz) fluctuations of the local field potential are mainly generated in the hippocampus and broadly distributed across the brain. This oscillation has been intensively studied using noninvasive (EEG and magnetoencephalography [MEG]) and invasive (electrocorticography) recording techniques (Herweg et al., 2020). It is linked with the integrative process for higher cognitive functions, such as memory retrieving and coding, working memory retention, novelty detection (Cavanagh & Frank, 2014), mental calculation, error processing, meditation, and emotion processing (Koelsch et al., 2004). Theta activation differs according to the cognitive control strategy employed (Eisma et al., 2021).

1.5.1 Affective Processing

Asada et al. (1999) stated that the anterior cingulate cortex (ACC) was one of the two sources of frontal midline theta rhythm (along with the medial prefrontal cortex). As part of the limbic system, the ACC is connected to the amygdala, hippocampus, and orbitofrontal cortex, primarily regulating emotional responses (Bush et al., 2000). In an EEG study of music and emotion (Sammler et al., 2007), participants were asked to rate their subjective feelings on the pleasantness of musical pieces. The results indicated that pleasant music was associated with increased frontal midline theta power.

1.5.2 Memory Processing

Remembering refers to forming associations between the sensory and cognitive experiences that comprise an event. This association is primarily in the medial temporal lobe that contains the hippocampus, entorhinal, perirhinal, and parahippocampal cortices. Theta oscillation is the physiological signature representing the communication and processing within these regions (Herweg et al., 2020). Klimesch et al. (1994) suggested that hippocampal neurons synchronize as a response to the demands of episodic memory increase. Consequently, the theta band increases.

1.6 Study Aims

This thesis aimed to determine the cause of color preference and uncover the mechanisms of color appreciation using behavioral and EEG analyses. First, behavioral research was conducted to speculate the cause of color preference. Chapter 2 presents the results of testing the hypothesis that color preference is induced by the mere exposure effect based on the information (memory and/or affect) from high-level cognitive processing. We identified the memory colors of mere exposed objects and investigated relationships between preference ratings and similarity of memory colors. Chapter 3 describes an EEG experiment to reveal brain activity during color appreciation, which was conducted to identify the process of color appreciation and examine whether appraising preferred and non-preferred colors exhibited similar patterns. Chapter 4 summarizes the results and discusses the current hypotheses along with the three theories mentioned above.

Color appreciation mechanism have been tested in previous behavioral studies; however, we used EEG to illustrate specific neural mechanisms and aimed to enrich extant research on mechanisms underlying color appreciation.

Chapter 2 Mere Exposure and Color Preference

2.1 Introduction

We aimed to investigate the hypothesis that color preference arises from mere exposure to colored objects. We examined the relationship between color preference and memory color created by mere exposure. Based on this relationship, a color preference prediction model was developed.

2.1.1 Mere Exposure Effect on Color

Mere exposure effect studies indicated that preference increased with the repetition of various stimuli and was sensitive to color information (Hupbach et al., 2006). Hupbach et al. tested the mere exposure effect on colors. Participants were asked to rate the match between the color and drawing without being informed about the later preference study. After a filler task that lasted 15–20 minutes to avoid short-term priming, participants were asked to select the most preferred colored drawing among four drawings on the screen, where the studied color was presented equally often in the four positions. The results demonstrated that the studied colors were chosen more often. They then conducted another experiment using different drawings for the two sessions. The results revealed that despite the shape change, there was still a mere exposure effect for colors.

Therefore, we can assume that when people are exposed daily to colored objects, there should be a mere exposure effect for the objects' colors. Furthermore, the preference toward the colors can be independent of the object and shape. For instance, one can prefer tomato-like color, even when this color is not presented in the context of a tomato but as an abstract color. This abstract memory color is stored in one's memory, creating a positive affect due to the mere exposure effect.

2.1.2 Modelling Memory Color

Yendrikhovskij et al. (1999) suggested three steps to form a prototypical memory color: sensation, perception, and generalization. First, people get the sensation of the objects in different contexts, such as different light sources and surroundings. This is followed by perception, which is a top-down input from the internalized object knowledge to form apparent object colors. Then, in the generalization stage, a general regularity of the prototypical object color is established. The prototypical color could be “the most representative attributes of the category” or its “central value” (p. 395), and this memory color is stored for later comparison and decision-making. Based on this assumption, the representation of memory color can be described using a multivariate probability function in perceptually uniform color spaces. As any object contains spots of different colors, the surface color should be distributed around a centroid with a density function. Previous studies successfully predicted the memory colors of real objects using a similar bivariate Gaussian probability density function (Babilon & Khanh, 2018; Smet et al., 2011; Smet et al., 2014). Objects’ colors were measured using a standard illuminant, and color variations were created around the objects’ colors. The object stimuli were either presented as images on a monitor (Smet et al., 2014; Yendrikhovskij et al., 1999) or using real objects under well-controlled lighting (Babilon & Khanh, 2018; Smet et al., 2011). Then, the Gaussian model described in Eq. (1) was applied to predict the memory colors based on observers’ similarity ratings for each stimulus.

$$\begin{aligned}
 f(x) &= a_1 + a_2 \cdot \exp\left(-\frac{1}{2}((x - \mu)^T \Sigma^{-1}(x - \mu))\right); \\
 \mu &= (a_3, a_4); \\
 \Sigma^{-1} &= \begin{bmatrix} a_5 & a_7 \\ a_7 & a_6 \end{bmatrix};
 \end{aligned} \tag{1}$$

where $x = (a^*, b^*)^T$ described the chromaticity of color stimuli; $\mu = (a_3, a_4)^T$ was the centroid of the bivariate distribution as well as the most likely location of memory color; and a_5 , a_6 , and a_7 defined the shape, orientation, and size of the distribution, respectively.

As the current study aimed to investigate general color preference, we tested the similarity of the presented color and their abstract memory color. It is known that perceptions of real object colors differ from those of color patches. For instance, people are more

sensitive to color changes in images of real faces than in color patches (Tan & Stephen, 2013). Another study showed that when manipulating colors on faces and shapes to represent emotional state, people tend to increase redness/yellowness more on shapes (Thorstenson et al., 2018). We expected that testing memory colors out of context would give the same tendency but higher chroma than real object colors.

2.1.3 Review of the Ecological Valence Theory

Our hypothesis regarding mere exposure is similar to that of the EVT (Palmer & Schloss, 2010), which states that color-associated objects are the critical information we rely on for the color preference decision. However, the EVT requires participants' affective response to the objects themselves: the more positive affect one experiences with the colored objects, the more they like the color. Conversely, mere exposure has no such requirement. Mere exposure requires only the implicit memory of the colors, even without recognizing the colored objects. For instance, one does not need to have a positive affect for tomatoes in order to like tomato-like color. Although Palmer and Schloss (2010) did not explain how the affective response to an object formed, one could recollect their good and bad experience with that object based on explicit memory or retrieve knowledge about the object based on implicit memory.

Based on the selection of stimuli, the EVT tested 32 categorical colors defined in four “cuts” (Saturated, Light, Muted, and Dark) and eight hues. Their experimental objectives were to show how preferences differed between the 32 categorical colors. As shown in Figure 1.3(A), there was an overall peak at the blue hue, which narrowed as chartreuse. Saturated colors were preferable to muted and light colors, and dark yellow and orange were significantly less preferred than other yellows and oranges. The EVT and other studies (Adams & Osgood, 1973; Saito, 1996; Zhang et al., 2019) that used a similar way of selecting color stimuli showed that specific categorical colors were preferred over others. Nevertheless, the preference for colors around categorical colors remains unclear. The current study investigated the mechanisms of color appreciation for unlimited colors on the color spectrum. These colors could be relatively seldom seen and hard to associate with objects; therefore, assessing the preference for these colors may not follow the same pattern as those of the categorical colors. As such, we created continuous color stimuli, deriving from a center color

and using a set interval. This allowed us to compare the preference for ambiguous colors that have not been tested in previous studies.

2.1.4 Study Approach

We hypothesized that there would be a relationship between color preference and memory colors of the mere exposed objects: the colors closer (more similar) to the memory colors in a perceptual uniform color space would be preferred, and vice versa. To test this hypothesis, we:

1. Predicted abstract memory colors of objects people are often exposed to;
2. Examined the relationship between color preference and memory color;
3. Created a color reference prediction model based on this memory-preference relationship; and
4. Investigated the potential mechanism behind color preference appraisal.

2.2 Experiment 1: Memory Color of Mere Exposed Objects

Experiment 1 aimed to identify the memory colors of commonly available objects. First, the chromaticity of five commonly seen objects was measured under illuminant D65. Then, color variations were created based on the measured chromaticity with a set interval along a^* , b^* , and L^* in *CIELAB* color space. Participants rated the similarity between each stimulus and their memory color of that object. The participants' ratings were used to model memory colors.

2.2.1 Methods

2.2.1.1 Participants

We recruited 38 students from Kanagawa University (18 males) with an average age of 22.8 ($SD = 2.8$) for the memory color experiment. Before the experiment, all participants were informed of the study purpose, and tested to have normal color vision with Ishihara

pseudoisochromatic plates (Ishihara, 2006). The study was approved by the ethics committee of Kanagawa University.

2.2.1.2 Stimuli

Five commonly available fruits and vegetables with colors spanning the whole hue circle were selected: tomato, potato, Japanese mustard spinach, blueberry, and eggplant. We measured the chromaticity of five items for each fruit and vegetable (for blueberries, five 100-gram packs were measured). Five values were collected from different measurement points for each item under illuminant D65 with colorimeter MINOLTA CS-100. Figure 2.1 shows the 25 values of fruits and vegetables with a *CIE 1931* chromaticity diagram.

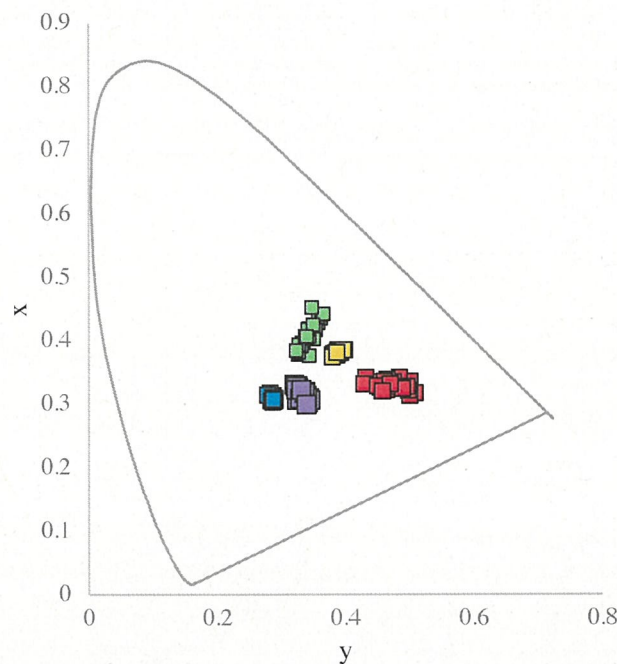


Figure 2.1. Measures of 25 points for each fruit and vegetable plotted in the xy -Plane of the *CIE 1931* chromaticity diagram. Red = tomato; yellow = potato; green = Japanese mustard spinach; blue = blueberry; purple = eggplant.

The 25 values were then averaged to produce a single reference color. Figure 2.2 shows the five reference colors recreated in *CIELAB* color space, and Table 2.1 describes their coordinates in *CIE 1931* and *CIELAB* color space.



Figure 2.2. Recreated reference colors for each fruit and vegetable in *CIELAB* color space

Table 2.1. *CIE 1931* coordinates of the reference color for each fruit and vegetable and their recreation along *CIELAB* coordinates

Objects	Reference color in <i>CIE 1931</i> color space			Recreated reference color in <i>CIELAB</i> color space		
	<i>x</i>	<i>y</i>	<i>Y</i> (cd/m ²)	<i>a</i> *	<i>b</i> *	<i>L</i> *
Tomato	0.47	0.33	48.29	60.76	28.29	74.74
Potato	0.39	0.38	76.10	9.56	31.27	90.03
Japanese mustard spinach	0.34	0.41	49.27	-18.67	30.13	75.45
Blueberry	0.29	0.31	31.64	-3.44	-9.44	62.84
Eggplant	0.33	0.32	22.81	10.88	-1.34	54.52

Based on the reference colors, we created eight color variations with the same interval of 20 along the *a** and *b** axes and another six steps on the *L** axis with an interval of ten in the

CIELAB space. Figure 2.3 shows the color variations created for tomato as an example (for the locations of all color variations in *CIELAB* color space, see Appendix A). In total, 15 color variations for each fruit and vegetable were created. All stimuli were presented on a 24" LCD monitor (BenQ XL2420T, 1920 x 1080 pixels), with a 4° x 4° visual angle on a light gray background (CIE $x = 0.312$, $y = 0.312$, $Y = 20.0$).

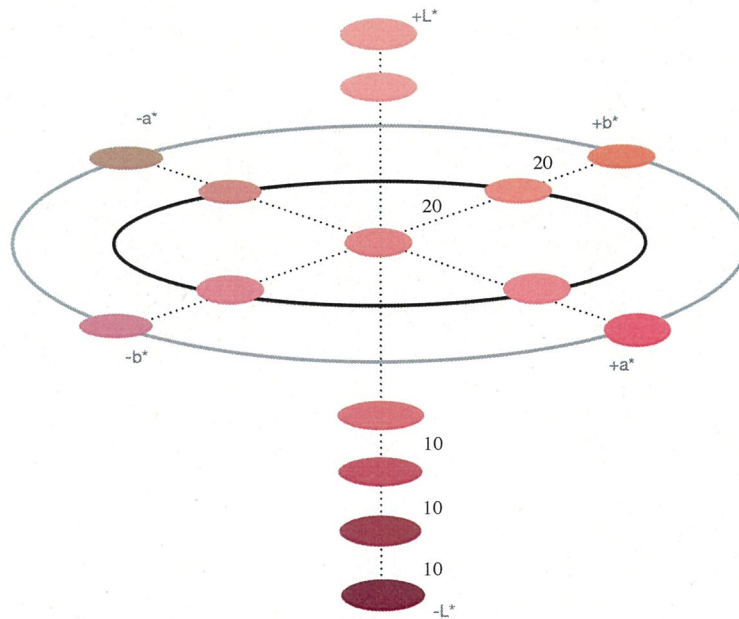


Figure 2.3. Color variations created for tomato. The color in the center is the average of the 25 measured colors for the 5 tomato samples. Color variations were created with two steps on each side of the original tomato color on the a^* and b^* axes (interval = 20) and another six steps along the L^* axis (interval = 10) in *CIELAB* space.

2.2.1.3 Procedure

Participants were seated 70 cm in front of the monitor in a dimly lit room. They had three trial tests before each experiment to understand the requirements. During trial tests for Experiment 1, we asked participants regarding the similarity between the presented color and their memory color of a peach. In the main experiment, participants sequentially assessed the similarity between the color stimuli and their memory colors for five fruits or vegetables (15 color variations for each fruit or vegetable). Participants assessed the similarity of each color

variation from 0%–100% by sliding the cursor on a visual scale. There was no observation time limit. After responding with a mouse click, there was a 500 ms interval (Figure 2.4). Each color was assessed twice, resulting in 150 trials (5 fruits / vegetables x 15 color variations x 2 repetitions). The experiment took approximately 20 minutes for each participant.

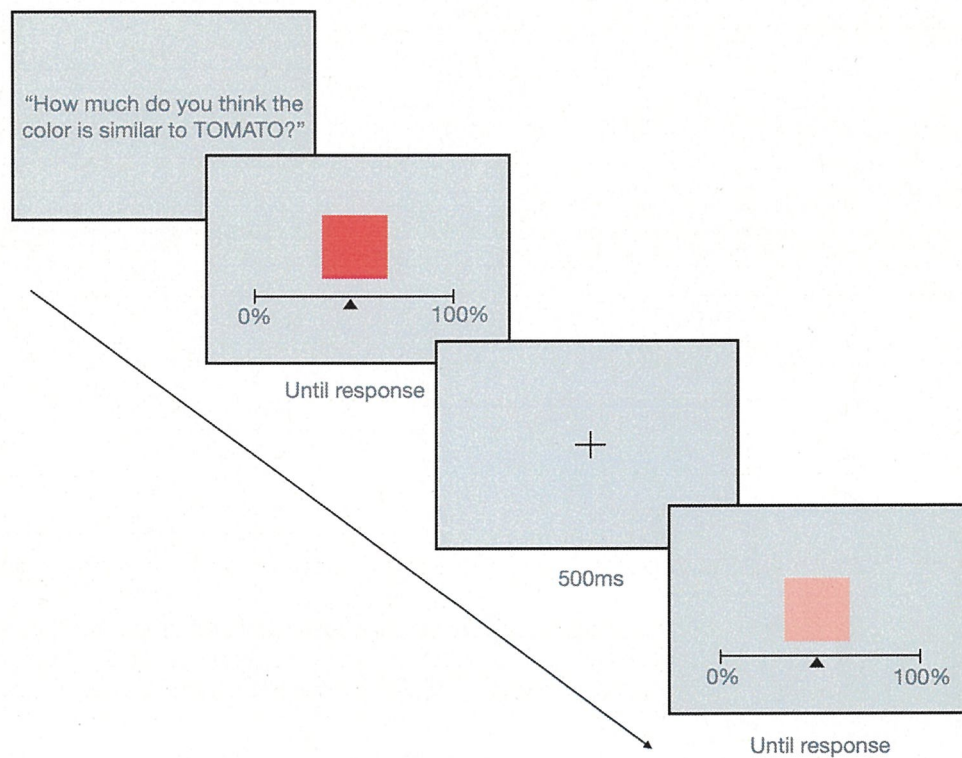


Figure 2.4. Procedure of Experiment 1: Memory color experiment

2.2.2 Results

Each stimulus was assessed twice by one observer, and similarity ratings were averaged for individual observers. The similarity ratings of all 38 observers were then averaged as the similarity ratings for one stimulus. A bivariate Gaussian probability density function Eq. (1) was fitted to the mean similarity for each fruit and vegetable as a function of *CIELAB a*b**. The results showed that the Gaussian model explained 86% of the variance for tomato and eggplant, 94% for potato and Japanese mustard spinach, and 92% for blueberry (Figure 2.5). There were significant correlations between the data predicted by the Gaussian model and the

pooled observers' data (all $p < .001$). The centroid of the Gaussian distribution served as the corresponding memory color on the a^* and b^* axes.

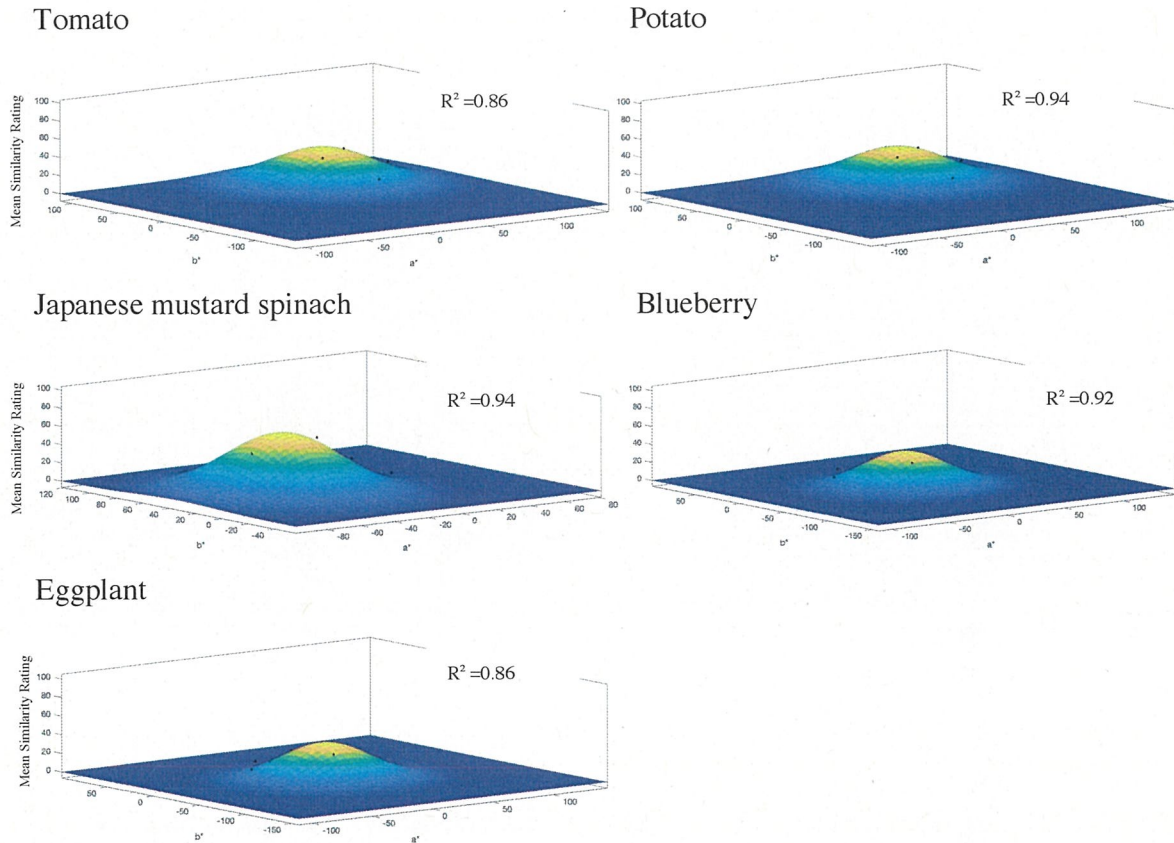


Figure 2.5. Bivariate Gaussian probability density function fitted for each fruit and vegetable. The horizontal axes are a^* and b^* . The vertical axis shows the mean similarity ratings pooled from observers' data. The black dots are the mean similarity rating of each color.

The mean of the similarity ratings on L^* was fitted with a one-dimension Gaussian function to determine the lightness of the memory color. The model explained 96% of the variance for tomato ($p < .001$), 72% for potato ($p = .015$), 97% for Japanese mustard spinach ($p < .001$), 86% for blueberry ($p = .002$), and 89% for eggplant ($p = .001$). Memory lightness was the peak of the Gaussian distribution (Figure 2.6). The predicted memory colors of all fruits and vegetables in the *CIELAB* space are presented in Table 2.2.

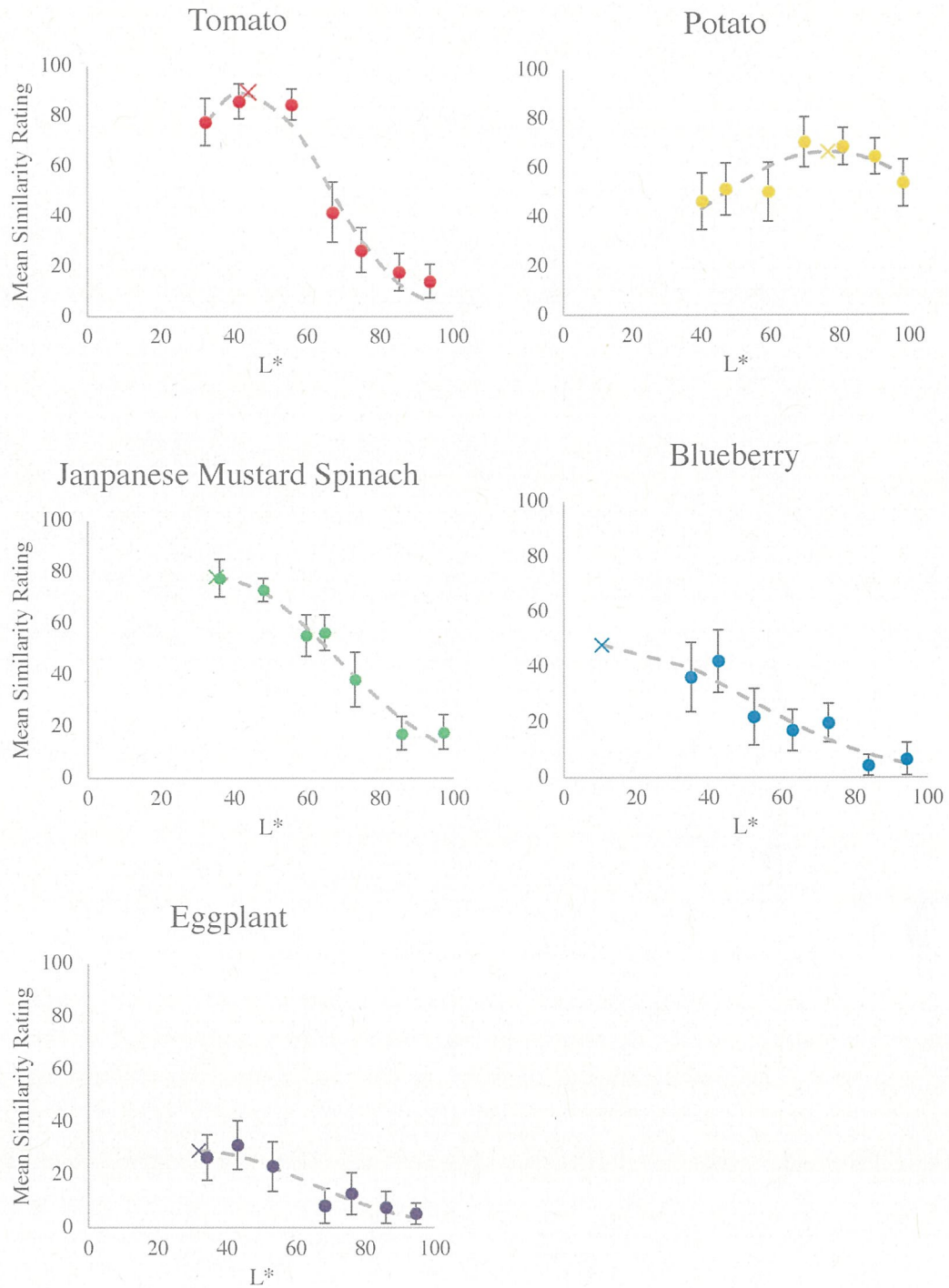


Figure 2.6. One-dimension Gaussian probability density function fitted for each fruit and vegetable for L^* . The crosses represent the predicted L^* . The dots are the mean similarity rating for each stimulus. Error bars represent standard errors.

Figure 2.7 compares the changes from reference colors under D65 illuminance to memory colors. The length of the arrows represents the chroma changes (ΔC_M). The memory colors had higher chroma than the colors measured under standard illuminants for all fruits and vegetables. The direction of the arrows represents the changes in hue angles (Δh). For tomato, potato, Japanese mustard spinach, and blueberry, the hue angles were shifted anticlockwise on the *CIELAB* plane. This indicated that tomato color was memorized as more orange, potato is more yellowish, Japanese mustard spinach more greenish, and blueberry is more purplish. Moreover, the hue angle was shifted clockwise for eggplant, meaning that eggplant was remembered as more blueish (the values of ΔC_M and Δh can be found in Table 2.2). Then, we drew the error ellipse, with a 0.50 probability that the position error would lie within it. We considered this to be the boundary of acceptance for the fruit or vegetable's color. The geometric measures of the ellipses are shown in Table 2.2.

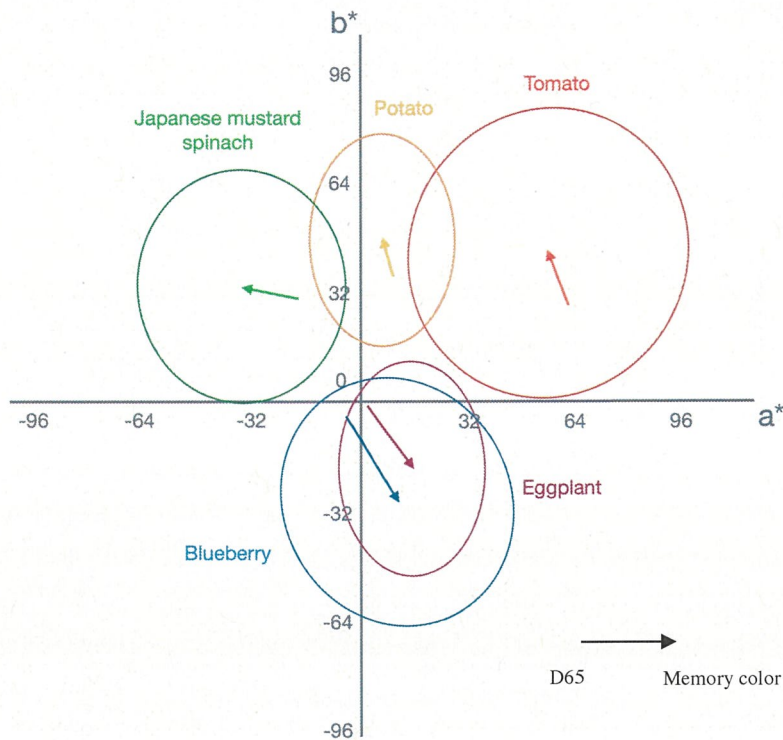


Figure 2.7. *CIELAB* coordinates of the predicted memory color and the boundary of acceptance for the fruit or vegetable's color. The arrows represent the chroma change from the reference colors under illuminant D65 to the predicted memory colors according to the a^* and b^* axes. The ellipses defined by the solid line show the acceptable boundary of the chromaticity for each fruit or vegetable.

Table 2.2. *CIELAB* coordinates for the memory color of each fruit and vegetable with chroma (ΔC_M) and hue angle (Δh) changes and the geometric measures of the error ellipse for each fruit and vegetable

Objects	L^*	a^*	b^*	ΔC_M	Δh	Semi-major axis	Semi-minor axis	θ
Tomato	53.87	55.06	43.28	20.32	13.18°	42.68	41.00	59.94°
Potato	76.62	6.09	46.86	34.11	9.29°	31.20	21.85	90.44°
Japanese Mustard Spinach	35.05	-35.33	33.51	33.39	15.04°	34.06	30.79	95.74°
Blueberry	20.44	10.75	-29.48	29.73	38.53°	35.55	33.59	158.78°
Eggplant	31.73	14.75	-19.77	22.10	-47.01°	31.00	22.82	91.39°

2.2.3 Discussion

Experiment 1 demonstrated that the Gaussian probability density function successfully predicted the memory colors of the objects. As in previous studies, memory colors tended to have higher chroma than reference colors measured under standard illuminants (Babilon & Khanh, 2018; Bartleson, 1960; Siple & Springer, 1983). The hue angles, in most cases, were shifted anticlockwise. The only memory color that was shifted clockwise was that of eggplant. Although it is unclear why purple objects were memorized as bluish, this result was consistent with Babilon and Khanh's (2018), where the memory color of the red cabbage was also shifted clockwise.

Furthermore, Experiment 1 revealed a difference in memory colors compared to the previous studies. Previous studies suggested that hue angles should shift toward the dominant hues associated with those objects (Babilon & Khanh, 2018; Bartleson, 1960). However, in the current study, the memory color of tomato shifted toward orange (instead of red), and blueberry shifted toward purple (instead of blue). We speculated that when participants were exposed to distinct appearances of the objects, their memory colors differed accordingly. Comparing the tomato color measured under illuminant D65 in Spain (Pérez-Carpinell et al., 1998), our measurement in Japan had lower chroma (Spanish tomato: $C = 75.77$; Japanese tomato: $C = 50.62$). Thus, exposure to a less reddish tomato would produce a less reddish memory color tomato. Babilon and Khanh (2018) measured blueberry color under illuminant

D56 in Germany. They plotted it in CIECAM02-UCS color space and predicted the memory color. The hue angle change was smaller (0.69°) than our measurements (38.53°), which indicated that the memory and reference color in Germany shared a similar hue. As Japanese observers were more familiar with processed blueberries, such as blueberry jam, sweets, and yogurt, which are more purplish than fresh blueberries, they tended to remember the color of blueberries as purplish (although we instructed participants to assess similarity with fresh fruit). Smet et al. (2014) demonstrated that memory colors of the same object could vary across regions. They tested the memory color of fruits, flowers, animation characters, and human skin in seven regions with colored images. Their results showed significantly different similarity ratings.

It is reasonable that being exposed to an object with distinct appearances would produce different memory colors. Next, we investigated whether the memory color affected color preference. If color preference changes according to memory colors, it can be proposed that color preference differs across regions, as object colors the observers are exposed to are distinct.

2.3 Experiment 2: Memory Color and Color Preference Association

Experiment 2 analyzed the relationship between memory color and color preference. Based on the memory colors obtained from Experiment 1, a set of color variations was derived for each fruit and vegetable with the same interval in *CIELAB* space. Participants rated their preference for each color variation. We hypothesized that the most preferred colors would be close to the memory colors of the fruits and vegetables. The color variations far away from the memory colors are the colors less likely to be fruits and vegetables' colors, so as less preferred colors.

2.3.1 Methods

2.3.1.1 Participants

A different group of 43 students (20 males) who did not participate Experiment 1 joined the color preference experiment. Their mean age was 21.3 (SD = 2.2). Before the experiment, all participants were informed of the purpose, and their color vision was tested to have normal color vision using Ishihara pseudoisochromatic plates (Ishihara, 2006). The study was approved by the ethics committee of Kanagawa University.

2.3.1.2 Stimuli

Based on the memory colors obtained from Experiment 1, we created another five sets of color variations for Experiment 2. A maximum of five steps along 12 directions were derived from the memory colors with the same interval (10) on the a^* and b^* axes. We obtained 188 stimuli (35 for tomato, 55 for potato, 24 for Japanese mustard spinach, 27 for blueberry, and 47 for eggplant) within the display's gamut. Figure 2.8 illustrates color variations derived from the memory color of potato as an example. The colored circle with "P" demonstrates the memory color calculated from Experiment 1, and the black dotted line represents the display's gamut. All stimuli were presented on a 24" LCD monitor (BenQ XL2420T, 1920 x 1080 pixels), with a 4° x 4° visual angle on a light gray background (CIE $x = 0.312$, $y = 0.312$, $Y = 20.0$).

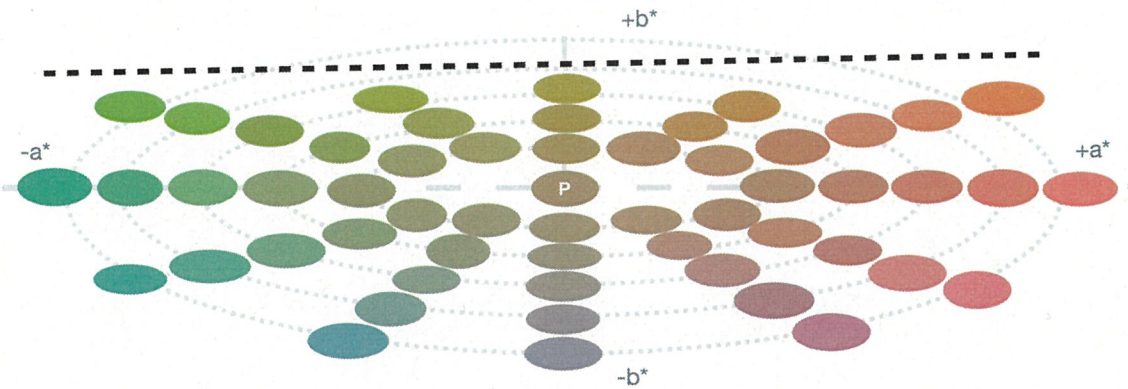


Figure 2.8. Color variations derived from the memory color of the potato. The black dotted line represents the display gamut.

2.3.1.3 Procedure

Participants were seated 70 cm in front of the monitor in a dimly lit room. They had three trial tests to understand the requirements. Participants assessed their preference toward 188 stimuli on a rating scale from “Not at all” to “Very much” by sliding the cursor on a visual scale. There was no observation time limit. After responding with a mouse click, there was a 500 ms interval (Figure 2.9). Each color was assessed twice, resulting in 376 trials. The experiment took approximately 20 minutes for each participant.

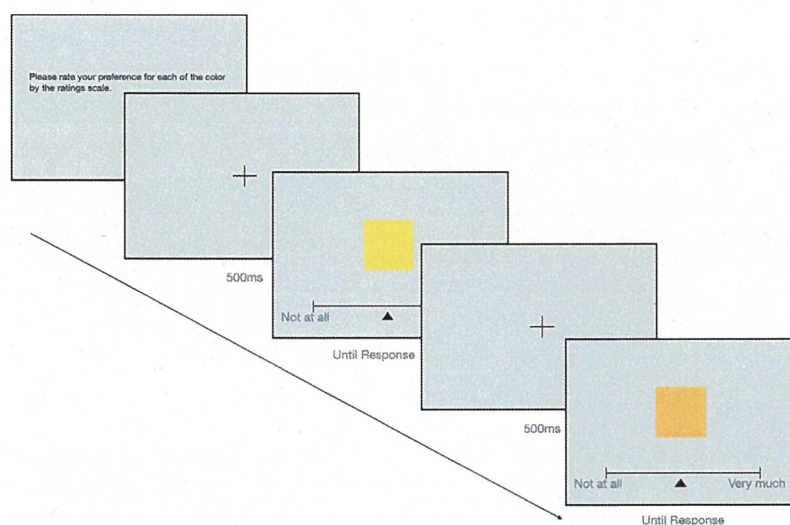


Figure 2.9. Procedure of Experiment 2: Color preference experiment

2.3.2 Results

2.3.2.1 Color Preference

We calculated the mean preference ratings of the colors (using the same method as calculating similarity ratings in Experiment 1) inside the acceptance boundary for each fruit and vegetable. Two different trends were found for red/yellow/green and blue/purple fruits and vegetables.

Tomato, potato, and Japanese mustard spinach. For the red/yellow/green fruits and vegetables, we found a significant non-linear regression between participants' preference ratings and a^* (Figure 2.10), whereas b^* was not significant. The following non-linear regression equations were obtained:

Tomato: $y = -0.0082x^2 + 0.6686x + 40.184$; $F [2, 27] = 29.09, p < .001, R^2 = .66$

Potato: $y = -0.0083x^2 - 0.0806x + 55.688$; $F [2, 25] = 26.23, p < .001, R^2 = .68$

Japanese mustard spinach: $y = -0.0144x^2 - 0.9046x + 45.671$; $F [2, 15] = 20.78, p < .001, R^2 = .74$

The locations of the most preferred colors on a^* were predicted: for tomato, $a^* = 40.77$; for potato, $a^* = -4.82$; for Japanese mustard spinach, $a^* = -31.41$. In Figure 2.10, vertical axes represent participants' averaged preference ratings. Horizontal axes represent the colors' location on a^* for tomato, potato, and Japanese mustard spinach. The red, yellow, green dots represent the memory colors of each fruit and vegetable. Cross signs show the predicted most preferred colors for tomato, potato, and Japanese mustard spinach.

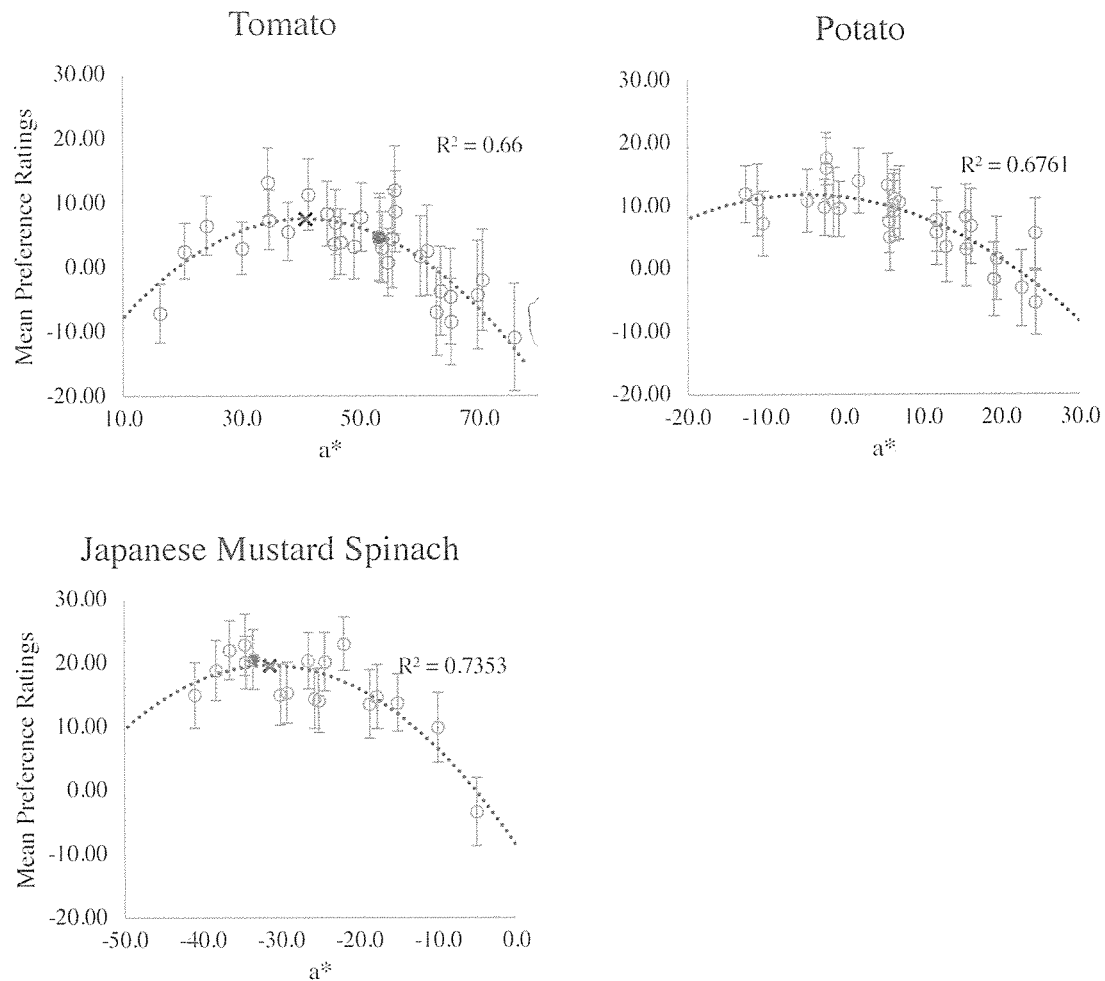


Figure 2.10. Non-linear regression predicting participants' preference ratings based on a^* axes for tomato, potato, and Japanese mustard spinach. Error bars show standard errors.

Blueberry and eggplant. Unlike the findings for the red, yellow, and green items, no significant association was found for the preference ratings of the blue and purple fruits and vegetables and a^* . In contrast, there was a significant linear regression between participants' preference ratings with b^* . The linear regression equations were as follows:

Blueberry: $y = -0.1916x + 50.285$; $F = [1, 20] = 19.72$, $p < .001$, $R^2 = .50$

Eggplant: $y = -0.2284x + 49.823$; $F = [1, 26] = 19.01$, $p < .001$, $R^2 = .42$

Participants preferred the colors with smaller b^* ; therefore, the most preferred colors were at the boundary of blueberry and eggplant. In Figure 2.11, vertical axes represent participants' averaged preference ratings. Horizontal axes represent the colors' location on b^* for blueberry, and eggplant. The blue and purple dots represent the memory colors of each fruit and vegetable.

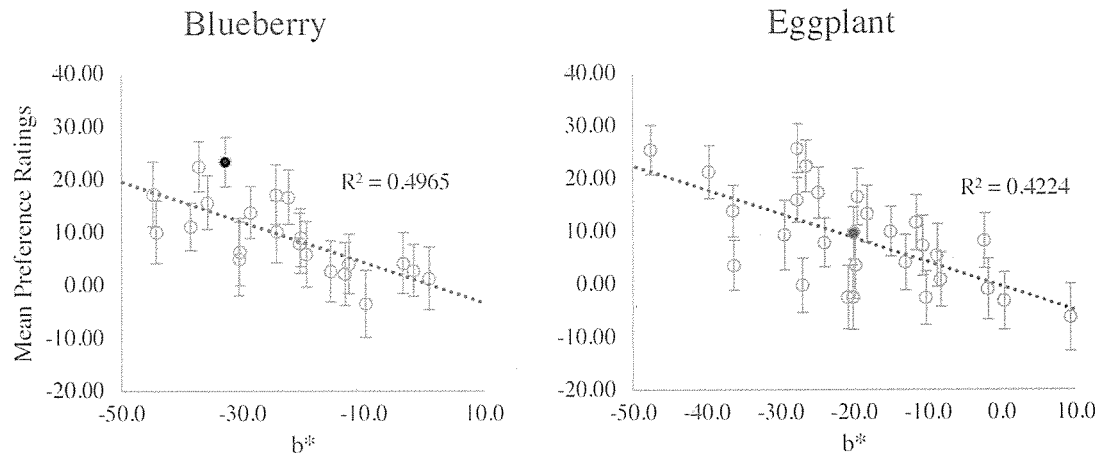


Figure 2.11. Linear regression predicting participants' preference ratings based on b^* axes for blueberry and eggplant. Error bars show standard errors.

We plotted the predicted most preferred colors onto the *CIELAB* plane and compared the locations with the memory colors (Figure 2.12). For tomato, potato, and Japanese mustard spinach, the most preferred colors were plotted with the shortest distance to the memory colors, which are the a^* (predicted by non-linear regression) with the same b^* as memory colors. The most preferred colors for tomato and Japanese mustard spinach were within 0.10 probability in the error ellipses; potato was within 0.20 probability. For blueberry and eggplant, the most preferred colors were predicted to have the smallest b^* ; therefore, they were at the boundary of that vegetable and fruit with the same a^* as their memory colors. The predicted most preferred colors were close to the memory colors for tomato, potato, and Japanese mustard spinach. The non-linear regression indicated that preference decreased as distance from the memory colors increased. This supported our hypothesis that people like colors that look similar to the memory colors of mere exposed objects. The preference

decreased when the colors became less similar. Moreover, this regression was only observed on a^* , which suggested that b^* did not play a crucial role in color preference judgment for those colors. In contrast, the regression on b^* was observed for blueberry and eggplant. Smaller b^* was associated with higher preference for the color, whereas a^* did not affect preference.

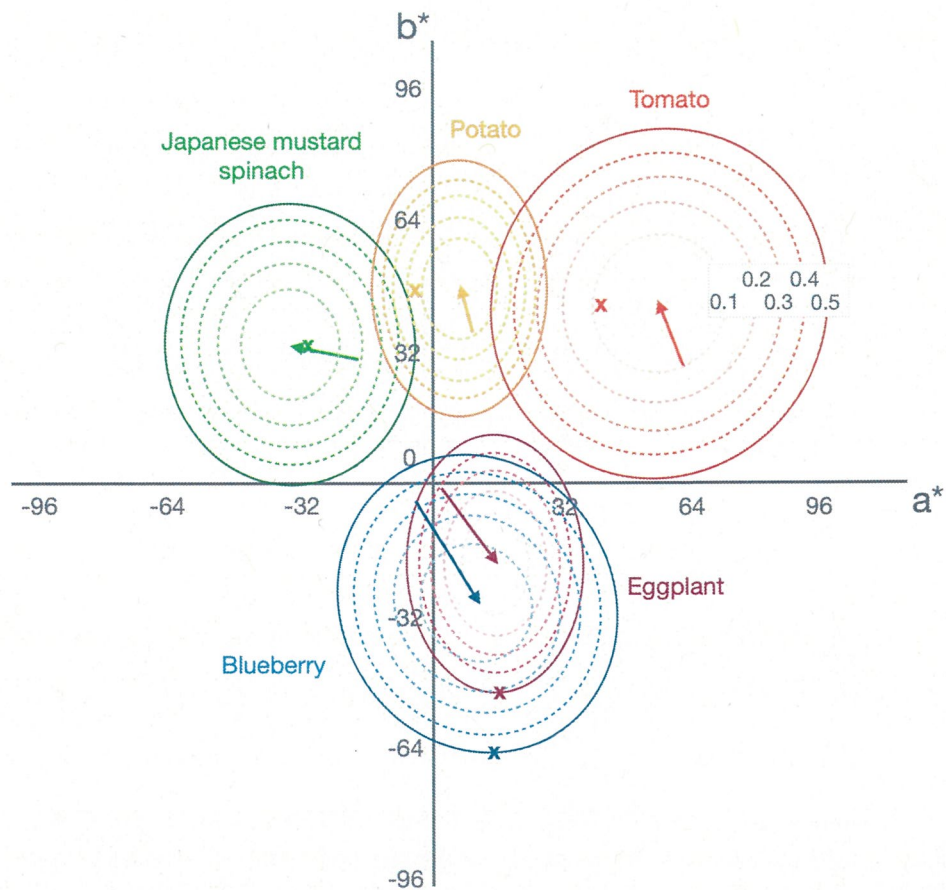


Figure 2.12. *CIELAB* coordinates of the predicted memory color and the most preferred color for each fruit and vegetable. The arrows represent the chromaticity change from the measured colors under illuminant D65 to the predicted memory colors according to the a^* and b^* axes. The crosses show the predicted most preferred colors with the shortest distance to the memory colors. The ellipses defined by the solid line show the acceptable boundary of the chromaticity for each fruit or vegetable. The dotted lines define the probability levels of the evaluation.

2.3.2.2 Modeling color preference

All objects contained a most preferred color, and regressions were observed between the most preferred and surrounding colors. Thus, the preference for a random color within the boundary could be predicted by its appearance: its location on *CIELAB* color space and its chroma and its relative location to the most preferred color. This could be described using a multiple regression model with the weighted sum of four individual components:

$$\text{Preference} = w_1 (a^*) + w_2 (b^*) + w_3 (C) + w_4 (\Delta C_P) + k$$

where a^* and b^* represent the color's location, $C (= \sqrt{a^{*2} + b^{*2}})$ represents the chromaticity of the color, and ΔC_P is the distance to the most preferred color within each vegetable and fruit, together with a constant k . This model explained 63% of the variance in our data ($F [4, 121] = 51.74, p < .001$). All variables made a significant contribution to the model (all $p < .001$; Table 2.3).

Table 2.3. Regression results for the color preference model

Variable	<i>B</i>	<i>SE</i>	<i>t</i>	<i>p</i>	95% CI
Constant	54.513	0.834	65.344	< .001	[52.86, 56.16]
a^*	-0.115	0.012	-9.935	< .001	[-0.14, -0.09]
b^*	-0.059	0.010	-6.137	< .001	[-0.08, -0.04]
<i>C</i>	0.112	0.019	5.889	< .001	[0.07, 0.15]
ΔC_P	-0.106	0.021	-5.143	< .001	[-0.15, -0.07]

The regression equation indicated that the preference for a random color within the object boundary was significantly predicted by its appearance and distance to the most preferred colors. As shown in Table 2.3, the model revealed the characteristics of the appearance of preferred colors. The negative weights on a^* and b^* with the positive weight on *C* indicated that the participants liked greenish and bluish colors with higher chroma. For the crucial distance to the most preferred colors, the negative weight on ΔC_P indicated that smaller distance was associated with preference for the color. The regression coefficient of b^*

was relatively lower than that of others, suggesting that the yellow-blue signal may have had less impact on color preference in the current data set.

2.3.3 Discussion

The findings from the present study partially supported our hypothesis. Mere exposure induced color preference for red, yellow, and green. However, no such effect was observed for purple and blue.

2.3.3.1 Ecology of color preference

The reason that red, yellow, and green were preferred differently from blue and purple could be due to ecological adaptation. According to Palmer and Schloss (2010), human color preferences are adaptive. Preference formation could occur on a shorter time scale, as an individual learning experience, or on a longer time scale related to evolution. Being attracted by colors that “look good” improves survival, reproduction, and general well-being. In the context of our study (fruits and vegetables), if a color is more likely to indicate ripeness (appetitive and containing more nutrition) than others or is more familiar (previously experienced), it is likely to attract people due to its associated benefits. Studies on monkeys have shown that the fruits they consume are colored red, orange, yellow, green, and brown (Gautier-Hion et al., 1985; Janson, 1983; Melin et al., 2014) (Figure 2.13), and monkeys’ trichromat vision has co-evolved with the colors of fruits. Monkeys use trichromat vision to judge ripeness by the appearance of the fruits. Fruit colors have morphed to increase the likelihood they will be consumed and have their seeds dispersed (Gautier-Hion et al., 1985; Mollon, 1989). It seems that a^* plays a crucial role not only in the detection of the fruits but also in forming preference for specific colors representing ripeness. Therefore, the non-linear regression we found for red tomatoes, yellow potatoes, and green Japanese mustard spinach is considered to represent the preference for colors representing ripeness.

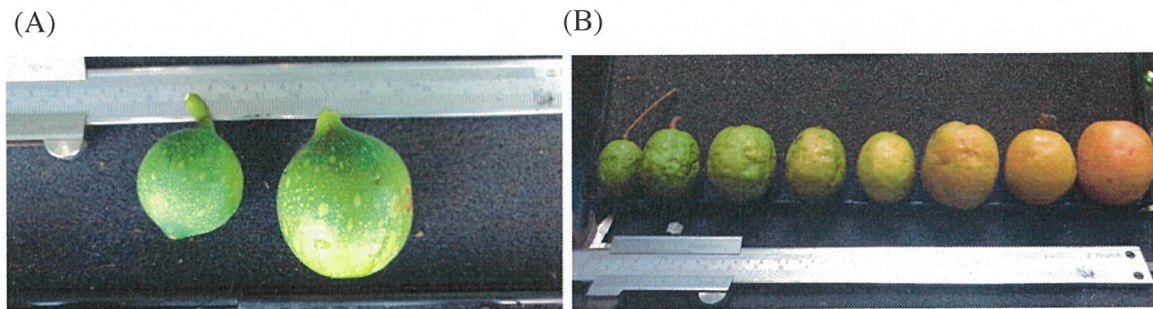


Figure 2.13. Sample photographs of (A) cryptic fruits and (B) conspicuous fruits for the mantled howler monkeys in Mexico. Cryptic fruits remain green, while conspicuous fruits change their colors to yellow, orange, and red during the ripeness stage. The photo was adapted from Sánchez-Solano et al. (2022).

As blue and purple fruits are so-called “bird fruit” (Janson, 1983) that primates do not rely upon, preferential judgments of these colors do not necessarily follow the same pattern as food colors. Palmer and Schloss (2010) argued that dark blue and dark purple, which were relevant to memory colors of blueberry and eggplant in the current study, were preferred because they are related to the objects such as dusk sky, ocean, plums, and grapes. However, those objects could only explain the preference for these two specific colors and not the negative regression whereby preference increased by decreasing b^* . Thus, further studies are required to uncover the mechanism between b^* and color preference.

2.3.3.2 Low-level color signal’s contribution to color appreciation

As repetition of stimuli induces positive affect, mere exposure effect can be seen as high-level processing of both memories and affect. Most color preference studies discussed only the high-level cognitive processing rather than the low-level color signal’s integration with it. The results of the current study showed how the two cone opponents of color were integrated with higher-level processing differently. For the red-green signal, the preferred colors were similar to specific memory colors on a^* ; for the yellow-blue signal, the smaller the b^* was, the more they were preferred. This indicated that the red-green signal was selectively integrated with the mere exposure effect for color appreciation.

Hurlbert and Ling (2007) emphasized the contribution of low-level cone opponents that the yellow-blue signal (44.5%) accounts for more variance than the red-green signal (25.5%) in their color preference data. However, they did not explain why the yellow-blue signal plays a more crucial role in color preference decisions. Furthermore, compared to the current results, whether people rely more on the red-green or yellow-blue signal depends on the appearance of the stimuli: for food colors (red to green), the red-green signal is essential, whereas for other colors, the yellow-blue signal is essential.

2.3.3.3 Comparing with the ecological valence theory

The current model explained 63% of the variance in our data obtained. In a study using the EVT tested with Japanese participants (Yokosawa et al., 2016), only 36% of the data variance was explained. The authors argued that Japanese people might relate colors to symbols and concepts more than the concrete objects provided in the EVT, weakening the prediction. Likewise, our model contained unexplained variances, and other factors, such as gender, age, personality, and personal experience, likely contributed to color preference. As mere exposure accounted for 63% of the variance, it should be considered essential. It can be concluded that mere exposure explains Japanese color preference better than the EVT. Furthermore, we expect that the model can be used to predict a more extensive range of color preferences by collecting more memory colors of mere exposed objects.

It must be noted that the current study did not compare the preference between fruits and vegetables. For instance, it did not compare the preference between tomato and potato colors. According to the EVT, this comparison could be explained by the experience one had with tomatoes and potatoes; therefore, it could be random according to individuals. The mere exposure explanation revealed a more detailed preference within the category, which could be applied to anyone as a more reliable predictor.

2.3.3.4 Cultural differences in color preferences

We found that the most preferred colors were close to the memory colors on a non-linear regression line for red to green objects. This indicated that color preference differed according to different memory colors. For instance, as Japanese and Spanish participants

generated different memory colors for tomatoes, it is reasonable to assume that they would prefer slightly different types of red. Similarly, Bonnardel et al. (2018) investigated color preference differences between British and Indian participants and found that Indian women had a warm bias, whereas British women showed the opposite. The authors claimed that adapting to natural environments with distinct surface reflectance and illuminants could lead to this bias. To add to their points, if Indian observers were more frequently exposed to objects, such as food and clothes, with warmer colors in their daily lives, they would find these colors more familiar and thus prefer them.

2.4 Conclusions

The results indicated that the mere exposure effect contributed to the color preference for red to green colors that belong to food, suggesting that color preference is adaptive and developed during the long-time evolution for better distinction of ripeness of fruits. In addition, during color preference appraisal, the lower-level color information (red-green or yellow-blue signal) integrated differently with high-level cognitive processing (mere exposure-related memory and affect) for the decision. Moreover, the current mere exposure model better predicted Japanese color preference than the EVT and explained potential cultural differences in color preference.

Chapter 3 Electroencephalogram Study of Color Appreciation

3.1 Introduction

The behavioral study presented in Chapter 2 examined the hypothesis that mere exposure induces color preference. Chapter 3 presents a study that measured the brain activity during color appreciation using EEG. This study aimed to suggest the cognitive process related with neural activity in different brain structures.

3.1.1 Theta Oscillations in Preferential Decision-Making

Studies have successfully indexed theta oscillations with specific preferential decision-making tasks. In an EEG study, Lindsen et al. (2010) asked participants to select the face they wanted to “approach and talk to” among two subsequently presented faces. The frontal theta band increased 500 ms after the second face was introduced, which was conspicuously left-lateralized if the second face was preferred. They suggested the frontal asymmetry was associated with processing positive affect or approach behavior (Davidson et al., 1990). A MEG study (Munar et al., 2012) showed a similar association between theta oscillation and aesthetic appreciation of images, including abstract images, realistic images, post-impressionist paintings, and photos of landscapes. Theta band for positive aesthetic experience (beautiful) was significantly greater than negative aesthetic experience (not beautiful) around 400 ms in the frontal and left temporal regions.

Moreover, studies have used the theta frequency band to predict consumers’ choice of their preferred products (Telpaz et al., 2015). The power in the theta frequency band in the midline frontal parts of the scalp for the least preferred products was significantly stronger than the most preferred products from 100 to 400 ms post-stimulus. Telpaz et al. (2015) suggested the stronger theta activity for least-preferred products could be due to the response

inhabitation. A go/no-go task, where participants were asked to respond to a go stimulus by pressing the designated key and avoid pressing the designated key when seeing a no-go stimulus, indicated that no-go responses were related to stronger frontal theta activity.

Frontal theta activity showed different patterns depending on the nature of the projects. Compared with the judgment of faces and images, color appreciation would be less similar to selecting preferred products since it would relate to a go/no-go purchase action. Thus, we expected the theta activation during the color appreciation would be more similar to the appreciation for faces and images.

3.1.2 Review of Color Preference Theories

Behavioral studies have argued regarding reasons that people prefer certain colors over others for decades; however, the results remain controversial. Color-emotion theory (Ou et al., 2004a, 2004b, 2004c) and the EVT (Palmer & Schloss, 2010) suggested that color preference appraisal involves affective processing in a bipolar negative-positive manner. Color-emotion theory states that color preference appraisal is based on the emotion evoked by the colors. Viewing preferred colors is associated with a positive affect, whereas viewing less preferred colors is associated with a negative affect. Preferred colors were described as active, light, cool, clean, and fresh, and disliked colors were described as passive, heavy, warm, stale, and dirty. In the EVT, color preference was associated with positive to negative affective valence of people's responses to the colored objects. The objects with the most positive affective valence included twilight sky, sunset, clear blue sky, and tropical ocean, whereas the objects with the most negative affective valence included feces, rotting fruits, urine, and vomit.

Furthermore, the EVT likely involves memory processing, as observers need to retrieve their experiences with that colored object, such as living experiences (Yokosawa et al., 2016), school life (Schloss et al., 2011), and political experiences (Schloss & Palmer, 2014). If color preference appraisal is an affective process or memory processing as these two theories suggested, we could expect the theta power measured by EEG to provide evidence.

3.1.3 Affective Processing and Hemisphere Asymmetry

Davidson et al. (1990) tested the hemispheric activation using short negative (disgust) and positive (happiness) film clips. They found that happiness was associated with the activation of the left anterior temporal frontal, and disgust was associated with right frontal and anterior temporal frontal regions. This result was consistent with the experiment using images with different emotional content from the International Affective Picture System (IAPS). There was a significant interaction between valence and hemisphere: theta band power was greater in the right anterior temporal regions when viewing negative stimuli, and greater in the left when viewing positive stimuli. The valence discrimination was shown to be 200–500 ms post-stimulus for positive, and 300–500 ms for negative affect (Aftanas et al., 2001).

3.1.4 Theta Oscillation and Memory Retrieval

Jacobs et al. (2006) examined subjects who viewed a list of consonants and were asked to indicate whether the probe was the target or a lure. Response accuracy and reaction times were recorded. The results showed that theta in the left parietal region related to memory retrieval and increased proportionally to how well the target was remembered. From 300 ms post-stimulus, theta power correlated with the degree of match between the target and probe stimulus, and from 500 ms post-stimulus, theta power could be used to predict whether it is a target or lure. Another study (Doppelmayr et al., 1998) asked the participants whether they studied the target words and found that good performers had greater theta synchronization (increase in band power) than bad performers over the right side of the brain. Good performers showed a laterality effect of large theta synchronization at the right hemisphere, whereas there was no hemisphere difference for bad performers. Thus, they concluded that theta synchronization was related to the “attempt to increase their retrieval accuracy” (p. 43).

3.1.5 Study Approach

We tested the hypothesis that color appreciation is an affective process. Viewing preferred colors related to positive affect would activate the left hemisphere; conversely, viewing non-preferred colors related to negative affect would activate the right hemisphere. A time-

frequency analysis on the theta band was performed to present the localization of neural activity and compare activities when appraising preferred and non-preferred colors.

Experiment 3: Theta Oscillations in Subjective Color Appreciation

In Experiment 3, participants rated their color preference, and their brain waves were recorded simultaneously. Brain activity while viewing preferred and non-preferred colors was compared.

3.1.6 Methods

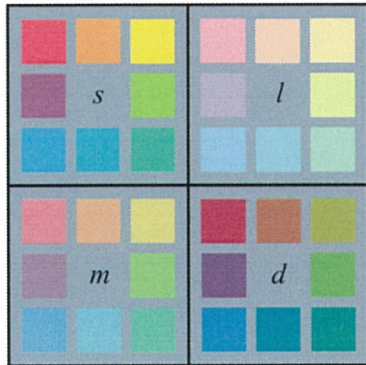
3.2.1.1 Participants

A total of 10 students (5 males) aged 22.4 ($SD = 4.6$) participated in the experiment. The participants were tested to have normal color vision using Ishihara pseudoisochromatic plates (Ishihara, 2006). The study was approved by the ethics committee of Kanagawa University.

3.2.1.2 Stimuli

Thirty-two colors from the Berkeley Color Project (Figure 3.1) were employed in the experiment. The colors were presented on a 24" LCD Monitor, approximately 4° of visual angle on a light grey background (CIE $x = 0.312$, $y = 0.312$, $Y = 20.00$). The monitor was characterized with MONOLTA CS-100 chroma meter. The CIE xyY coordinates for the stimuli can be found in Table 3.1.

(A)



(B)

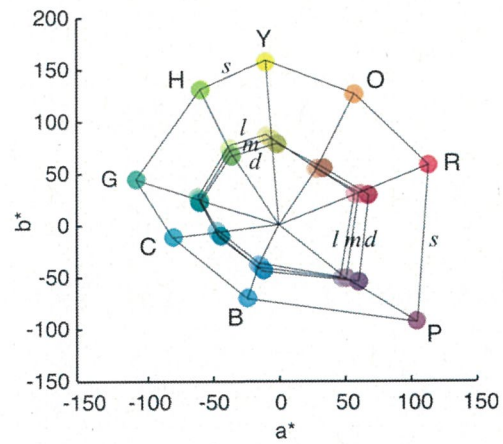


Figure 3.1. Thirty-two colors from the Berkeley Color Project tested in Experiment 3. (A) shows the 32 colors that represented eight hues in four “cuts” (s–saturated; l–light; m–muted; d–dark); (B) shows the projections of the 32 colors on in *CIELAB* color space. The figures were adapted from Palmer and Schloss (2010).

Table 3.1. CIE 1931 values for the 32 colors

Color	x	y	Y (cd/m ²)
Saturated Red (SR)	0.543	0.313	22.16
Light Red (LR)	0.405	0.328	49.82
Muted Red (MR)	0.446	0.331	22.06
Dark Red (DR)	0.508	0.314	7.57
Saturated Orange (SO)	0.516	0.420	48.82
Light Orange (LO)	0.400	0.370	67.24
Muted Orange (MO)	0.430	0.381	33.90
Dark Orange (DO)	0.493	0.393	10.554
Saturated Yellow (SY)	0.441	0.475	90.70
Light Yellow (LY)	0.393	0.416	91.72
Muted Yellow (MY)	0.407	0.425	49.00
Dark Yellow (DY)	0.432	0.444	18.04
Saturated Chartreuse (SH)	0.383	0.509	67.06

Light Chartreuse (LH)	0.354	0.422	77.66
Muted Chartreuse (MH)	0.361	0.434	42.54
Dark Chartreuse (DH)	0.371	0.485	18.34
Saturated Green (SG)	0.269	0.449	42.68
Light Green (LG)	0.287	0.382	62.62
Muted Green (MG)	0.282	0.396	96.16
Dark Green (DG)	0.268	0.428	12.06
Saturated Cyan (SC)	0.230	0.332	48.74
Light Cyan (LC)	0.264	0.331	68.34
Muted Cyan (MC)	0.254	0.323	33.28
Dark Cyan (DC)	0.231	0.324	12.74
Saturated Blue (SB)	0.198	0.230	34.38
Light Blue (LB)	0.252	0.273	58.20
Muted Blue (MB)	0.242	0.259	28.74
Dark Blue (DB)	0.210	0.228	10.26
Saturated Purple (SP)	0.273	0.152	18.26
Light Purple (LP)	0.287	0.245	49.14
Muted Purple (MP)	0.282	0.221	22.42
Dark Purple (DP)	0.282	0.181	7.192

3.2.1.3 Procedure

Participants were seated 70 cm in front of the monitor in a dimly lit room. They assessed the preference for the 32 colors. Each trial started with the presentation of a fixation cross for 500ms, followed by the color stimulus for 1000 ms. Participants then rated their preferences by a visual scale from “Not at all” to “Very much.” A numeric pad controlled the cursor. Participants pressed “4” and “6” with their index finger and ring finger to the left and right side of the scale, respectively, and pressed “5” with the middle finger to confirm their ratings (Figure 3.2). Each color was assessed ten times randomly. EEG was recorded during the assessment with EMOTIV EPOC X. The electrodes are located at the positions AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 (14 channels, sampling rate = 256 Hz)

according to the International 10–20 system. The experiment took approximately 30 minutes for each participant.

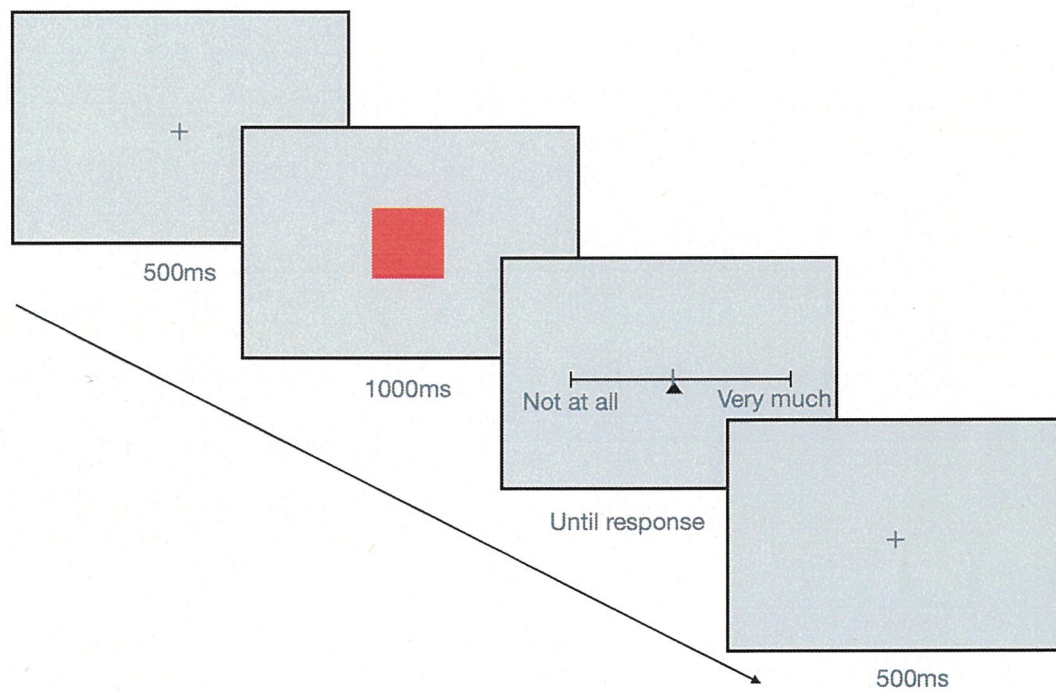
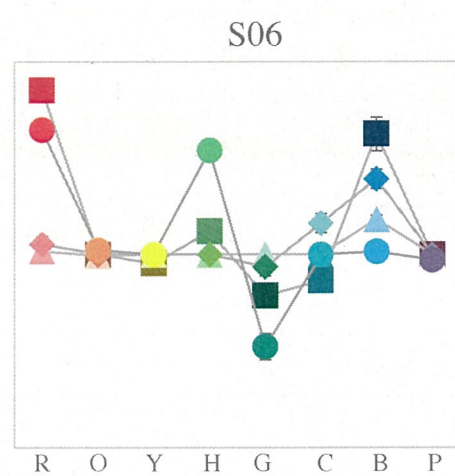
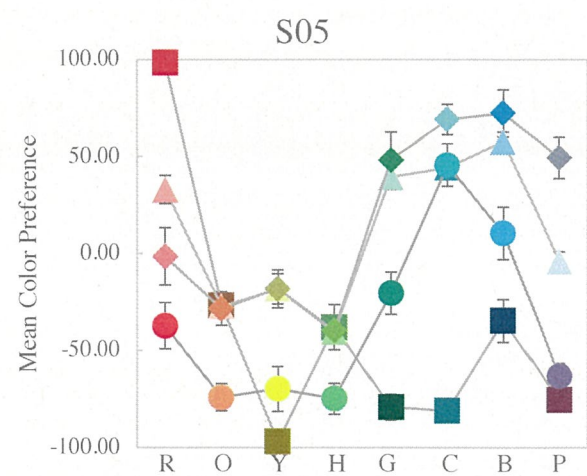
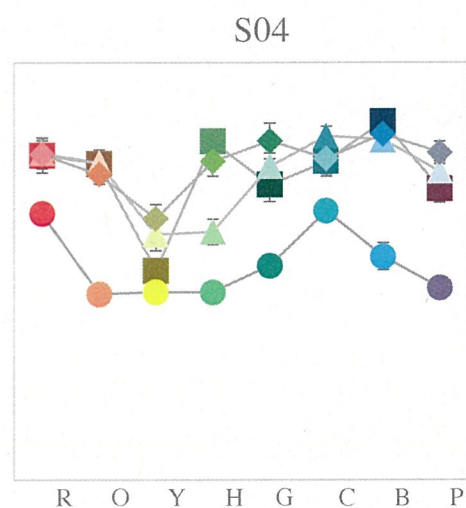
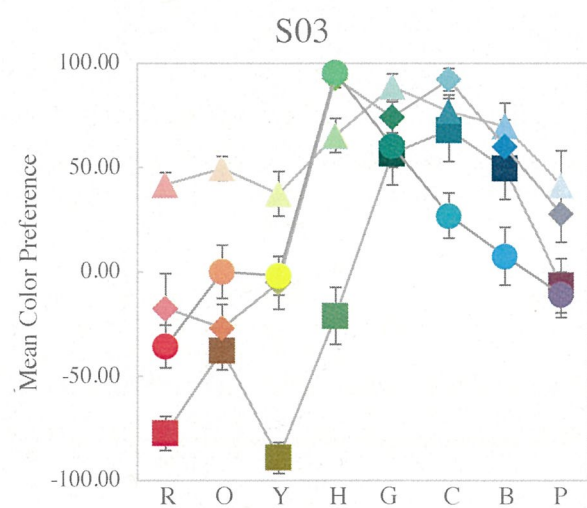
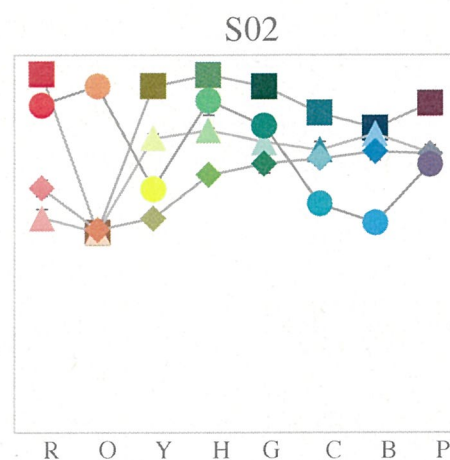
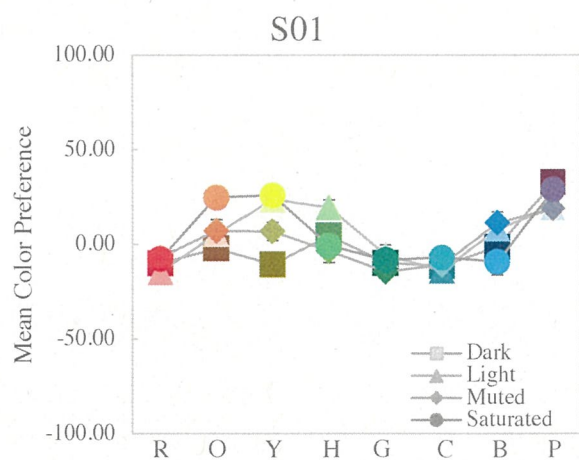


Figure 3.2. An illustration of the experimental procedure of Experiment 3

3.2.1.4 Data processing

For the behavioral data, the mean preference ratings for each stimulus were calculated. Figure 3.3 illustrates the mean color preference for each participant. The ten most highly rated colors for each participant were grouped as “Preferred,” and the ten lowest rated colors were grouped as “Non-preferred” (Appendix C).



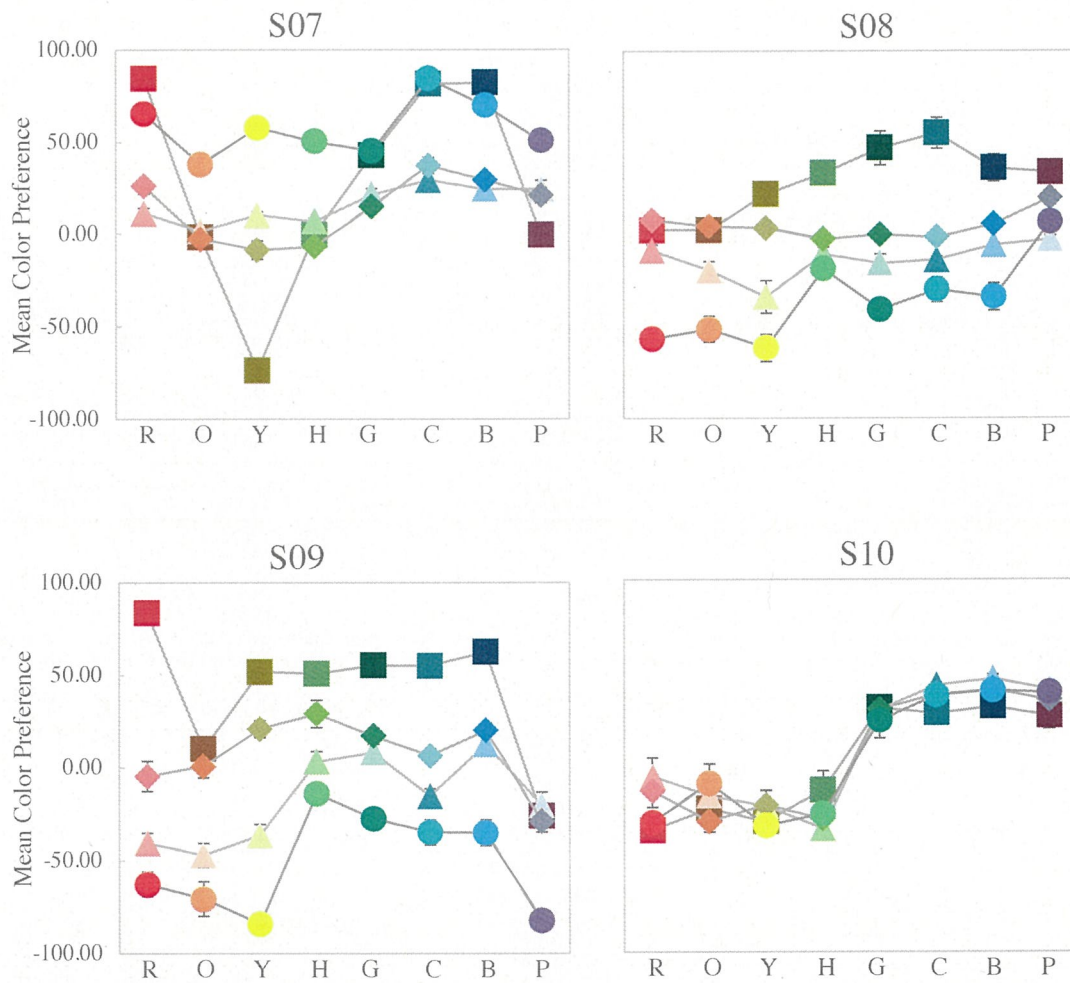


Figure 3.3. Mean color preference of the 32 BCP colors for each participant. The horizontal axis represents the color name (R: red, O: orange, Y: yellow, H: chartreuse, G: green, C: cyan, B: blue, P: purple). The vertical axis represents the averaged preference ratings for ten times. The four shapes represent four cuts of BCP colors (rectangle: dark cut, triangle: light cut, diamond: muted cut, circle: saturated cut). Error bars are standard errors.

The EEG data were high-pass filtered at a cutoff frequency of 0.5 Hz. Subsequently, a cutoff frequency at 50 Hz low-pass filter was applied to remove the line noise. Artefact was discarded after visual inspection. Independent component analysis (ICA) was conducted to remove the eye blinking and muscle activity. Consequently, in the preferred group, the

number of epochs was 588 (for each participant, $M = 59$, $SE = 5$); in the non-preferred group, the number of epochs was 567 (for each participant $M = 57$, $SE = 6$). Time-frequency analysis was performed for the frequency band of theta (4-8 Hz). The spectral power was calculated by averaging over the constituent frequencies during 200–500 ms from the stimulus onset. Figure 3.4 shows the electrocap layout. The ten electrodes highlighted in green were grouped into four regions in the analysis: left frontal (AF3, F7, F3, FC5), right frontal (AF4, F8, F4, FC6), left posterior (P7, O1), and right posterior (P8, O2). A two-way analysis of variance (ANOVA) was performed with region (4: left frontal, right frontal, left posterior, and right posterior) and preference (2: preferred and non-preferred). The Bonferroni correction was used in *post hoc* analysis conducted for pairwise comparisons, provided that the main effect was found.

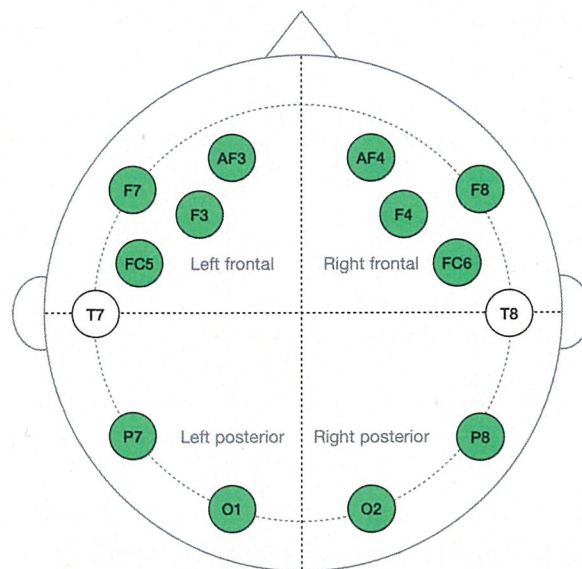


Figure 3.4. The electrocap layout of EMOTIV EPOC X

3.1.7 Results

Figure 3.5 shows mean theta power (4-8 Hz) from 200 to 500 ms stimulus onset. The scalp map shows the distribution viewing the ten non-preferred colors (A) and ten preferred colors (B). According to the map, the differences were primarily located in the left frontal part of the scalp: when viewing preferred colors, the left frontal regions were activated, whereas when viewing non-preferred colors, neither the left frontal nor right frontal region was activated.

Instead, activation was observed in the left posterior region. Figure 3.5 (C) further compares the theta power in the left frontal region following stimulus onset. Between 200 and 500 ms post-stimulus period, preferred colors induced a larger amount of theta power than non-preferred colors and peaked at approximately 300–350 ms.

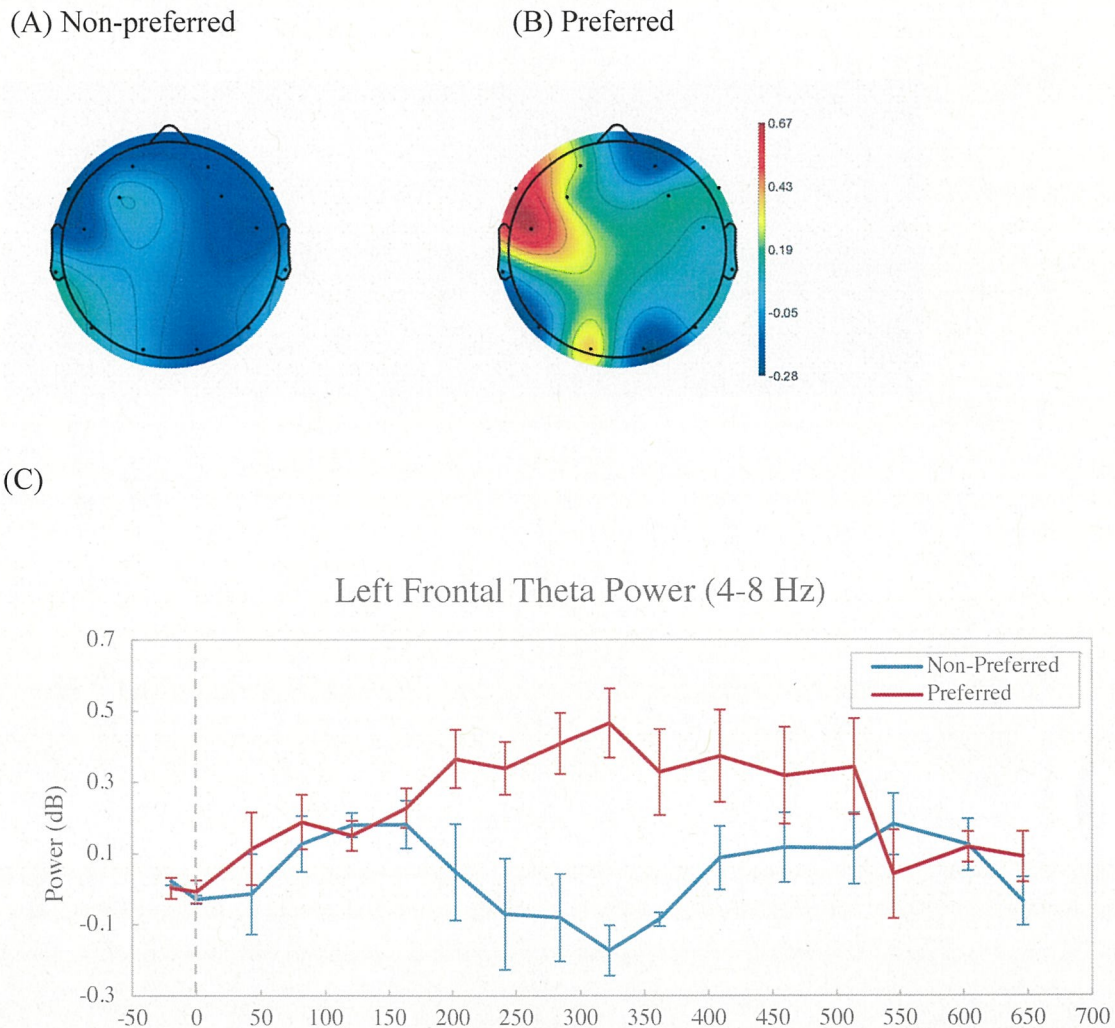


Figure 3.5. Scalp distribution of power in the theta band (4-8 Hz) from 200 to 500 ms stimulus onset when viewing (A) non-preferred and (B) preferred colors. (C) Theta power (in dB) averaged over the electrodes of the left frontal region (AF3, F7, F3, and FC5). Between 200 and 500 ms stimulus onset, data yielded significant differences between viewing preferred (blue line) and non-preferred colors (red line). The dotted line represents stimulus onset. Error bars represent the standard error.

The ANOVA results revealed a significant main effect of preference ($F [1, 448] = 23.703, p < .001$) and region ($F [3, 448] = 120.720, p < .001$). In addition, a significant interaction effect of both factors was found ($F [3, 448] = 141.842, p < .001$) (Table 3.2). To investigate the interaction effect, an analysis of simple main effects was conducted. Pairwise comparison tests showed that viewing preferred colors induced greater theta power in the frontal regions (left frontal: $t[112] = 24.205, p < .001$; right frontal: $t[112] = 4.731, p < .001$) and weaker theta power in the posterior regions (left posterior: $t[112] = -9.073, p < .001$; right posterior: $t[112] = -2.739, p = .007$).

Table 3.2. Theta power (in dB) observed in different regions when viewing preferred and non-preferred colors

Region	Preferred		Non-preferred	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Left Frontal	0.387	0.009	-0.068	0.013
Left Posterior	0.217	0.037	0.458	0.002
Right Frontal	0.066	0.009	-0.048	0.008
Right Posterior	0.195	0.054	0.277	0.011

Pairwise comparison of the theta power in different regions revealed that when viewing preferred colors, there was an apparent frontal theta asymmetry effect. Theta power was significantly greater in the left frontal than in the right frontal region and posterior regions (all $p < .001$), whereas there was no difference found between left and right posterior regions (Figure 3.6A; Table 3.2). In contrast, viewing non-preferred colors did not induce a difference between left and right frontal regions. Theta power in the left posterior region was significantly greater than in the right posterior and in the two frontal regions ($p < .001$; Figure 3.6B; Table 3.2).

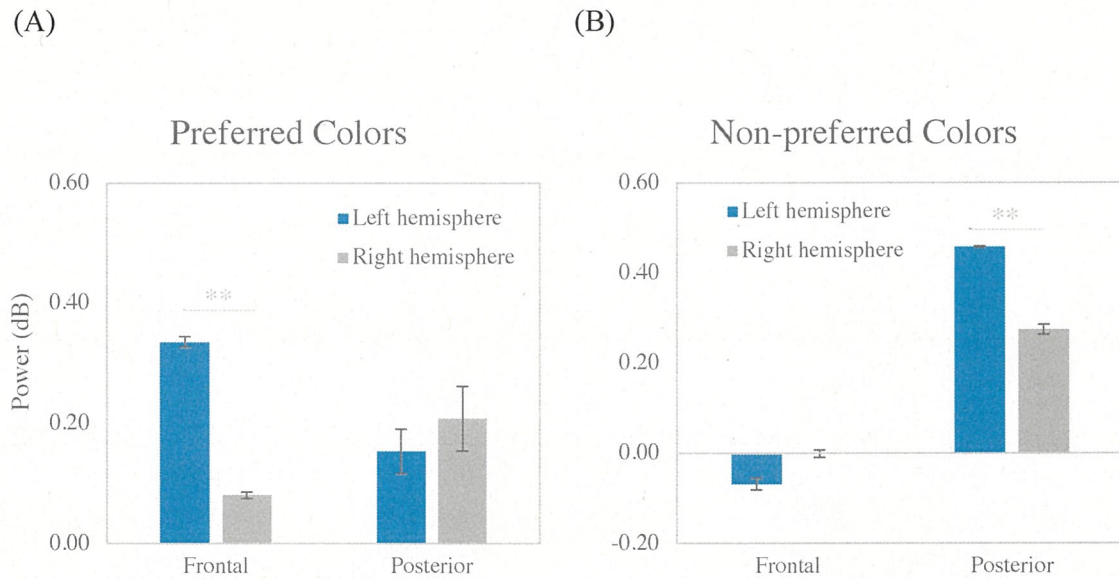


Figure 3.6. Power in theta band in left and right hemispheres when viewing (A) preferred and (B) non-preferred colors. Left frontal theta power was averaged from AF3, F7, F3, and FC5 electrodes. Right frontal theta power was averaged from AF4, F8, F4, and FC6. Left posterior theta power was averaged from P7 and O1. Right posterior theta power was averaged from P8 and O2. Error bars represent standard errors. The asterisks represent the significant differences (** $p < .001$).

3.1.8 Discussion

This EEG experiment revealed the neural activity underlying the appreciation of preferred and non-preferred colors. The time-frequency analysis showed two patterns of brain activity in the theta band and indicated that the activated areas differed.

There was an apparent frontal theta asymmetry when viewing preferred colors. The theta band power was significantly greater in the left frontal region than in the right. This indicated that viewing color preference was associated with processing positive affect. Damasio (1996) suggested that decision-making is not necessarily only but primarily by emotional quality. In their neural affective decision theory, Litt et al. (2008) explained that decision-making is a cognitive-affective process. It is not a “cold” mathematical calculation of the expected values but depends on the emotional evaluation. The results of the current

The results of the current study agreed with the suggestion that appraising for preferred colors is an affective process. This process was similar to appraising approachable faces (Lindsen et al., 2010) when left frontal theta power was activated. However, viewing non-preferred colors did not relate to a negative affect, as the right hemisphere was not activated. This result differs from the color-emotion theory and the EVT, which suggest that people do not like the colors due to the negative emotion or negative affect they had on those colors or colored objects.

Rather, the activation of left posterior regions suggested that appraising non-preferred colors might relate to memory retrieving. Although it is unclear type kind of memory the observers were retrieving, there could be two assumptions. Yeh et al. (2015) suggested that the observers compared their sensory representation with previous experiences when doing the appraisal. Furthermore, observers might try to retrieve the ratings they gave in the previous sequences. This could be seen as the observers' strategy in the color appraisal task when they did not have affect to support their decision.

Whether appraising preferred and non-preferred colors share a similar experience remains a question. This has been suspected in behavioral studies. Strauss et al. (2013) asked participants to rate their color preference, then asked them to evaluate their preference for colored objects (positive and negative red and green objects). The color preference ratings were retaken to compare how the color preferences change. Results showed that the preference ratings significantly increased after exposure to the positive valenced pictures (e.g., preference for red increased after exposure to strawberries). In contrast, no significant change was observed after exposure to the negative valenced picture (e.g., preference did not decrease after exposure to pond scum). They suggested that observers might not want to focus on unpleasant pictures during the experiment to minimize negative emotions. The current study suggested that unlike preferred colors, appraising for non-preferred colors is not an affective process; therefore, the affective experiences did not reshape the color preferences.

The differences in brain activity were also observed when appraising everyday designed products with positive and negative emotional content. In an fMRI experiment, Yeh et al. (2015) asked the observers to rate the products by the degree of beauty (ugly, medium,

and beautiful) and their “aesthetic emotions” toward those products (negative, neutral, and positive). When the products were beautiful and had positive emotions, the right ACC, which is crucial in emotional responses and regulation, was activated. However, 2.667% of the beautiful products were assessed as a negative emotion. When the beautiful products were related to a negative emotion, the precuneus that links to episodic memory retrieval was activated. They concluded that appreciation for products with emotionally negative and positive contents was a response to different cognitive and affective mechanisms.

3.2 Conclusions

The EEG study described distinct activation patterns when appraising preferred and non-preferred colors. It is suggested that our brains assess color preferences in a different manner. Appraising preferred colors activated the left frontal regions related to positive affect processing, whereas appraising non-preferred colors activated the left posterior regions involving the memory retrieving process.

Chapter 4 General Discussion

4.1 Summary of the Main Findings

This thesis investigated the cause and mechanism underlying color preference appreciation by both behavioral and EEG studies. We propose that the mere exposure effect is the main cause of color preference, and there are distinct mechanisms for appraising colors based on preference. The details of this proposal are compared with those of the three previous color preference theories from Ou et al. (2004a, 2004b, 2004c), Hurlbert and Ling (2007), and Palmer and Schloss (2010).

Chapter 2 introduced a behavioral study that found two relationships between color preference and memory colors: 1) from red to green, the positive affect induced by mere exposure leads to color preference. There was a non-linear regression found between color preference ratings and a^* , which suggested that observers liked the colors that were closer to the memory colors; and 2) for blue and purple colors, there was a negative relationship found between color preference and b^* , which indicated that observers preferred the colors looked bluer. Furthermore, a color preference prediction model that explained 63% of the variance was proposed. Based on the results, we proposed the mechanism of color preference appraisal: a high-level cognitive process (memory and affect) integrates with the lower-level color information (red-green or yellow-blue signal) differently (based on whether the colors relate to food) for the color preference decision. As a^* had a crucial contribution to the food colors, we also hypothesized that color preference was adaptive and evolved over a long timescale to distinguish the fruits' ripeness.

Chapter 3 measured the brain activity when doing color preference appraisal. A time-frequency analysis showed distinct activation patterns when appraising preferred and non-preferred colors. Appraising preferred colors was an affective process, and the theta oscillations in the left frontal area significantly increased during the 200 to 500 ms post-stimulus. As such, observers choose their preference based on their affective responses to

those colors. Conversely, appraising non-referred colors was a memory-retrieving process that the left posterior theta activation was observed. The results suggested that appraising preferred and non-preferred colors relies on different mechanisms.

4.2 Implication of the Findings

4.2.1 Mere Exposure Induced Affect and Color Preference

In Chapter 2, we discussed that mere exposure induces a positive affect; therefore, colors are preferred when they are closer to the memory colors. When the color becomes less similar, less positive affect exists, and preference reduces accordingly. It can be concluded that preferred colors are related to positive affect, whereas non-preferred colors are related to less positive but not negative affect. This result is consistent with Chapter 3, where the EEG study showed a left frontal theta activation when appraising preferred colors. Moreover, there was no right laterization of theta activation for non-preferred colors. This suggested that the observers were conducting affective processing while viewing preferred colors but not non-preferred colors. As there was an insufficient positive affect for non-preferred colors, observers could not rely on affect to make the preference decision and relied on another mechanism to retrieve their memory with that color for the decision.

Hence, color preference appreciation is not a bipolar affective evaluation, as suggested by the EVT (Palmer & Schloss, 2010) and color-emotion theory (Ou et al., 2004a, 2004b, 2004c), where positive affect and emotions related to preferred colors and negative affect and emotions related to non-preferred colors. Color preference relies on two distinct processes for preferred and non-preferred color appreciation. It is plausible to suggest that colors, as an everyday visual experience, might not produce a negative affect on our brains.

4.2.2 The Mechanisms of Color Appreciation

Based on the results of the current experiments, the mechanism of color appreciation that was suspected in Chapter 1 was updated (Figure 4.1). Unlike the three theories discussed above, color preference is not defined only by early sensory processing, the two cardinal dimensions

of opponent cone-contrast as suggested by Hurlbert and Ling (2007), or only by the high-level cognitive process, emotions and affective responses to colors or objects as indicated by Ou et al. (2004a, 2004b, 2004c) and Palmer and Schloss (2010). Instead, appreciation of colors is an affective process in which early sensory information in a manner of the two cardinal dimensions of opponent cone-contrasts is selectively integrated with higher-level cognitive information for the decision: the red-green signal integrates with mere exposure-induced positive affect, and the preferred colors are similar to the mere exposed colors. Conversely, the yellow-blue signal integrates with the positive affect but differently, as the bluer the colors, the more they were preferred. Moreover, when no positive affect arises toward the colors, people try to leverage a memory process for the decision.

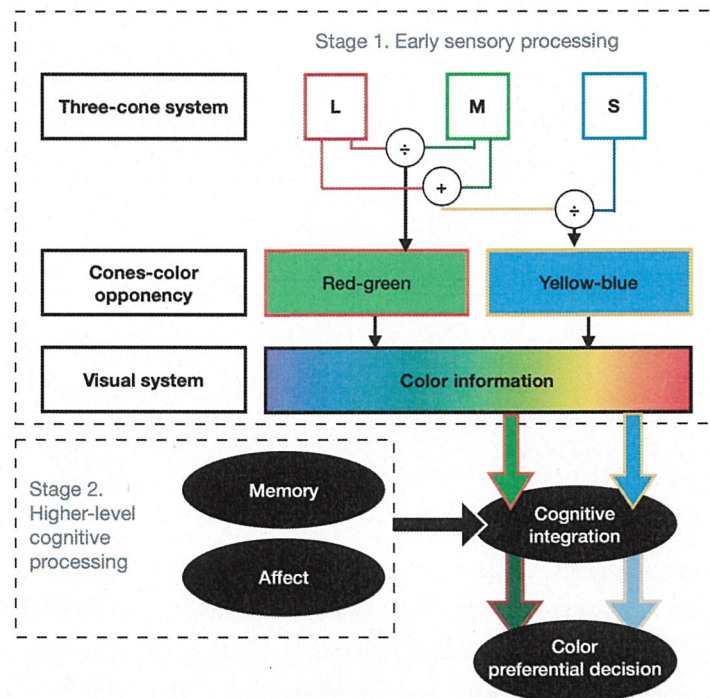


Figure 4.1. Diagram depicting the mechanism of color appreciation

4.2.3 Color Preference Developed in Evolution

This study agrees with the theories proposed by Hurlbert and Ling (2007) and Palmer and Schloss (2010), suggesting that color preferences are adaptive and evolved for human well-being. However, there are some disagreements. Hurlbert and Ling emphasized the hunter-

gatherer theory in their study based on their data that female participants preferred reddish color to men. They suggested women's preference for red was wired in their biological component during evolution, as they were responsible for collecting ripe fruits. Although we did not discuss gender differences in the current study, we would like to propose a more delicate function that governs all human beings to find the most appropriate fruits. This system does not focus on whether a red hue is preferred but distinguishes the most desirable colors from food colors (from red to green).

Furthermore, the current study agrees with Palmer and Schloss's (2010) suggestion that people like the colors that "look good" to them and dislike the colors that "look bad." The differences come from how to interpret "look good." This indicates whether the colors are associated with liked objects. The current study would emphasize that it is related to whether they are appetitive. As Palmer and Schloss said, it is a mechanism tuned in the human brain for survival and reproductive success.

4.3 Considerations for Further Research

4.3.1 Yellow-blue Signal's Contribution to Color Appreciation

As suggested, the red-green signal was integrated with the mere exposure effect for the color preference decision. However, we could not confirm why the yellow-blue signal defined the color preference in a different manner. Hurlbert and Ling (2007) emphasized the yellow-blue signal (44.5%) accounts for more variance than the red-green signal (25.5%) in their preference data. However, they did not explain why the yellow-blue signal plays a more crucial role in color preference decisions and why people prefer bluer colors. Furthermore, compared to the current results, whether people rely more on the red-green or yellow-blue signal depends on the location and appearance of the stimuli.

A blue-yellow color signal derived by dividing the output of the luminance signal ($L+M$) by the output of the S cones: $S/(L+M)$. S cones are phylogenetically and physiologically unique to L and M cones. From an evolutionary perspective, mammals are dichromatic with only two spectrally distinct classes of single cones: short-wave-sensitive

and long-wave-sensitive. Only primates recently acquired trichromacy, whereas Old World monkeys had separate gene codes for long-wave-sensitive and middle-wave-sensitive cone pigments (Bowmaker, 1998). In psychophysical studies, S cones are less numerous than L and M cones, and there are no S cones in the central fovea. In addition, S cones exhibit little or no projection to the superior colliculus, which means that involuntary attentional shifts do not require signals from the S cones. It is worth investigating how S cones contribute to higher-level cognitive visual tasks, such as color preference judgment.

To test S cones' contribution to color preference, ask observers to assess their color preferences with suppressed S cones – “transient tritanopia” (Smithson et al., 2003). The S opponent channel is polarized by exposing the observers to a steady yellow field, and this causes a loss of sensitivity to short-wavelength stimuli. The color stimuli must be selected along the tritanope confusion line. On each line, the S cones have the same level of involvement in color perception. The S cones are desensitized entirely, and the participants depend only on the L/M signal along the theoretical tritanope confusion line. Then, we must compare how the color preference changes by different S cones' involvement levels.

Two hypotheses can be proposed: 1) If S cones contribute more to the overall color preference decision, by canceling the function of S cones, color preference will become flattened. That is, there will be no significant preference difference between each color. 2) If S cones mainly contribute to the preference for bluish and purplish colors, the preference for bluish and purplish colors will decrease, but there will be no significant impact on red to green colors.

4.4 Conclusions

This thesis conducted behavioral and EEG studies to uncover the underlying mechanism of color appreciation. Three main conclusions can be drawn from the finding. First, appraising preferred colors is an affective process. Two cardinal dimensions of opponent cone-contrasts from the early level sensory stage integrate with higher-level cognitive information differently to decide preferred colors. The red-green signal is especially selectively integrated with the mere expose-induced positive affect. Second, unlike preferred colors, appraising

non-preferred colors is a distinct process. When no affect arises from viewing colors, observers need to rely on the memory to retrieve their experience. Third, as the mere exposure effect was observed for those red to green “food colors,” it can be suggested that color preference is adaptive and developed during the long-time evolution for better distinction of ripeness of fruits. In the future, more in-depth research on the contribution from the early sensory level, especially S cones, is required.

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Appendix A Similarity rating and location of *CIELAB* color space for stimuli in Experiment 1

Color Name	CIELAB color space			<i>Mean</i>	<i>SE</i>
	<i>L</i> *	<i>a</i> *	<i>b</i> *		
Blueberry 1	62.8	-3.4	-9.4	27.3	3.8
Blueberry 2	63.4	-19.5	-7.9	17.0	3.1
Blueberry 3	63.1	-34.1	-6.8	11.6	2.4
Blueberry 4	62.2	17.2	-8.6	31.8	4.0
Blueberry 5	61.0	39.0	-8.5	16.6	3.2
Blueberry 6	62.6	-1.5	-28.9	34.5	4.1
Blueberry 7	60.2	1.7	-48.4	30.3	4.5
Blueberry 8	62.3	1.0	9.2	9.5	2.2
Blueberry 9	62.6	-2.6	30.2	8.4	2.1
Eggplant 1	54.5	10.9	-1.3	35.9	4.8
Eggplant 2	53.7	-8.1	-1.1	15.2	3.2
Eggplant 3	53.3	-28.6	-0.9	8.6	2.4
Eggplant 4	54.1	30.5	-1.3	23.4	3.9
Eggplant 5	55.5	51.3	-1.6	11.6	3.3
Eggplant 6	55.0	10.0	-21.1	57.3	4.6
Eggplant 7	46.0	8.2	-35.9	34.8	4.2
Eggplant 8	53.1	11.4	18.6	17.2	3.6
Eggplant 9	53.3	10.1	38.7	13.7	3.6
Potato 1	90.0	9.6	31.3	60.7	3.9
Potato 2	89.7	-8.9	30.4	35.3	4.1
Potato 3	90.4	-28.1	31.6	12.5	2.7
Potato 4	91.2	31.0	32.1	19.1	3.1
Potato 5	90.9	50.1	31.5	11.5	2.4
Potato 6	89.4	12.2	12.1	21.8	3.2
Potato 7	88.6	12.0	-8.3	10.2	2.1
Potato 8	91.5	10.9	53.0	58.3	4.5

Potato 9	91.0	11.3	72.1	40.7	4.7
Spinach 1	75.5	-18.7	30.1	55.9	3.7
Spinach 2	75.8	-37.4	26.7	57.5	4.1
Spinach 3	76.0	-57.3	29.7	46.8	4.3
Spinach 4	76.0	5.0	26.2	12.8	2.5
Spinach 5	75.2	24.4	29.0	8.2	2.0
Spinach 6	75.0	-15.6	7.7	38.7	4.0
Spinach 7	73.9	-13.8	-11.5	7.3	1.6
Spinach 8	74.8	-14.9	47.7	38.2	4.2
Spinach 9	75.8	-15.1	69.0	24.6	3.6
Tomato 1	74.7	60.8	20.0	40.2	4.4
Tomato 2	75.1	40.3	28.0	34.1	4.3
Tomato 3	75.9	21.8	-15.0	20.6	3.1
Tomato 4	76.9	80.5	-24.8	24.8	3.8
Tomato 5	74.0	95.8	-13.0	20.3	4.7
Tomato 6	76.2	58.6	-24.0	17.6	2.8
Tomato 7	74.0	58.6	-8.7	15.0	2.7
Tomato 8	75.9	61.9	-27.7	35.6	4.3
Tomato 9	75.0	61.6	-8.2	33.0	4.4

Appendix B Preference rating and location of *CIELAB* color space for stimuli in Experiment 2

Color Name	CIELAB color space			<i>Mean</i>	<i>SE</i>
	<i>L</i> *	<i>a</i> *	<i>b</i> *		
Blueberry 1	23.2	11.3	-32.7	23.44	4.68
Blueberry 2	20.9	11.6	-20.5	8.03	5.71
Blueberry 3	22.9	10.8	-9.6	-3.45	6.38
Blueberry 4	20.7	11.5	0.9	1.35	5.92
Blueberry 5	22.6	11.8	9.6	-0.36	6.39
Blueberry 6	20.2	3.4	-24.5	17.28	5.65
Blueberry 7	21.2	17.4	-24.4	10.21	5.85
Blueberry 8	21.4	19.0	-35.7	15.77	5.09
Blueberry 9	19.5	28.6	-19.4	5.97	6.22
Blueberry 10	19.4	28.0	-38.5	11.17	4.52
Blueberry 11	22.5	38.4	-15.4	2.71	5.79
Blueberry 12	20.8	35.8	-44.2	10.19	5.92
Blueberry 13	20.8	45.9	-50.5	6.43	6.16
Blueberry 14	22.3	5.1	-22.4	16.79	5.15
Blueberry 15	19.9	15.0	-37.1	22.56	4.74
Blueberry 16	20.9	14.4	-20.4	9.14	5.48
Blueberry 17	18.4	22.4	-44.7	17.36	6.14
Blueberry 18	22.2	21.3	-13.0	2.21	5.94
Blueberry 19	21.2	0.8	-12.4	4.09	5.63
Blueberry 20	19.3	-4.2	-3.4	4.26	5.76
Blueberry 21	18.8	26.7	-1.6	2.90	4.91
Blueberry 22	19.8	30.9	3.7	1.84	5.70
Blueberry 23	22.3	-11.1	6.3	9.00	5.00
Blueberry 24	20.4	-13.5	12.8	7.69	4.93
Blueberry 25	22.1	18.2	-28.6	13.90	4.93
Blueberry 26	22.7	32.6	-30.5	5.07	7.00
Blueberry 27	24.3	37.9	-30.3	6.43	6.37

Eggplant 1	30.7	14.5	-20.0	9.69	4.91
Eggplant 2	32.0	54.2	-20.1	-4.28	5.53
Eggplant 3	30.0	13.3	-27.7	16.00	4.25
Eggplant 4	30.1	16.7	-39.7	21.27	5.00
Eggplant 5	32.0	14.2	-47.6	25.51	4.68
Eggplant 6	31.6	14.5	-10.2	-2.63	5.05
Eggplant 7	29.5	15.6	0.4	-3.22	5.46
Eggplant 8	30.0	15.7	9.4	-6.33	6.38
Eggplant 9	31.4	4.3	-19.5	16.56	5.39
Eggplant 10	30.1	15.0	20.0	-4.99	5.66
Eggplant 11	32.6	15.2	28.0	-8.52	6.49
Eggplant 12	31.8	5.9	-15.0	9.99	4.71
Eggplant 13	31.2	5.3	-24.8	17.35	4.85
Eggplant 14	30.4	23.3	-13.0	4.15	5.23
Eggplant 15	31.6	20.1	-24.0	7.90	4.63
Eggplant 16	30.5	-3.2	-8.7	5.45	5.95
Eggplant 17	29.5	0.2	-27.7	25.77	4.65
Eggplant 18	30.4	28.3	-8.2	0.87	5.17
Eggplant 19	31.6	32.3	-29.5	9.33	6.60
Eggplant 20	30.1	-6.8	-18.2	13.33	5.39
Eggplant 21	30.1	-8.4	-4.2	7.29	5.91
Eggplant 22	30.4	37.7	-4.4	-0.21	5.09
Eggplant 23	31.7	38.0	-33.9	11.66	6.31
Eggplant 24	31.3	-20.5	0.9	13.86	4.44
Eggplant 25	32.3	46.6	0.0	3.60	4.83
Eggplant 26	31.3	46.1	-37.8	8.21	6.56
Eggplant 27	31.5	59.8	-44.9	-0.95	7.01
Eggplant 28	31.4	7.5	-26.5	22.41	4.91
Eggplant 29	30.4	8.5	-10.7	4.44	5.66
Eggplant 30	29.8	17.3	-27.0	14.97	5.13
Eggplant 31	32.1	19.9	-11.6	-1.03	5.22
Eggplant 32	30.4	23.7	-36.4	20.03	4.91
Eggplant 33	30.9	7.8	-36.3	22.94	4.73
Eggplant 34	30.4	23.3	-2.3	0.12	5.17
Eggplant 35	32.6	3.8	-1.8	-2.21	5.76
Eggplant 36	31.9	-1.3	6.0	-0.41	6.61

Eggplant 37	32.1	31.1	5.8	2.26	4.97
Eggplant 38	30.2	25.0	-44.3	14.03	4.79
Eggplant 39	31.1	32.0	-53.1	14.06	5.26
Eggplant 40	32.0	34.5	15.5	0.42	5.03
Eggplant 41	31.5	-4.0	14.8	-6.44	5.61
Egg Plant 42	31.3	37.2	-61.1	11.48	6.27
Eggplant 43	31.6	39.7	22.2	5.08	4.62
Eggplant 44	30.3	-11.3	22.9	5.14	5.58
Egg Plant 45	30.3	24.8	-20.1	8.10	6.13
Eggplant 46	30.4	34.9	-19.8	3.60	6.35
Eggplant 47	29.6	46.6	-20.8	-2.48	6.02
Potato 1	76.3	6.5	48.5	11.02	4.65
Potato 2	77.6	45.5	47.9	-14.09	8.12
Potato 3	78.1	55.6	47.9	-15.98	8.09
Potato 4	77.9	6.2	36.6	10.05	5.02
Potato 5	77.7	5.8	26.3	4.97	5.32
Potato 6	77.4	5.7	17.5	7.50	5.04
Potato 7	77.1	7.7	6.5	15.43	6.99
Potato 8	76.6	6.0	-2.0	22.85	6.84
Potato 9	75.8	6.4	56.3	9.13	4.77
Potato 10	75.4	5.5	66.3	13.22	5.08
Potato 11	75.8	7.0	75.1	10.44	5.84
Potato 12	76.4	-2.5	46.9	9.72	4.47
Potato 13	75.9	-2.3	51.7	17.49	4.16
Potato 14	76.3	-1.3	43.0	10.60	5.50
Potato 15	77.5	15.5	52.5	8.16	5.14
Potato 16	76.5	13.1	42.6	3.33	5.54
Potato 17	76.1	-10.3	55.9	7.21	5.13
Potato 18	76.4	-11.0	35.8	10.98	5.73
Potato 19	75.4	24.3	57.6	5.49	5.61
Potato 20	78.2	22.6	41.2	-3.21	6.06
Potato 21	77.3	-12.6	45.8	11.92	4.55
Potato 22	75.1	-17.0	62.4	8.36	4.60
Potato 23	76.6	-20.6	30.1	17.36	5.71
Potato 24	77.5	31.3	59.5	-7.36	6.96
Potato 25	74.8	28.9	32.1	-0.87	6.54

Potato 26	78.9	-28.2	69.8	24.68	8.20
Potato 27	79.0	-28.6	25.4	14.84	6.91
Potato 28	76.3	36.5	68.3	-8.76	7.07
Potato 29	78.3	40.8	27.0	-7.92	8.11
Potato 30	77.0	-38.3	71.2	6.15	6.54
Potato 31	77.6	-35.6	22.8	11.35	7.63
Potato 32	77.3	-25.1	47.0	16.27	6.22
Potato 33	75.9	48.4	77.7	-9.36	8.01
Potato 34	78.9	51.4	21.6	-13.30	9.09
Potato 35	76.7	1.8	39.1	13.94	5.15
Potato 36	77.7	-0.6	56.3	9.49	4.43
Potato 37	76.5	11.8	39.6	7.70	5.07
Potato 38	76.3	11.8	53.9	5.63	5.08
Potato 39	78.0	19.1	29.4	-1.77	5.90
Potato 40	75.3	-2.3	28.5	15.94	4.84
Potato 41	76.4	16.2	64.8	6.65	5.97
Potato 42	78.6	-4.7	64.3	10.83	5.01
Potato 43	75.5	-35.3	47.2	17.38	5.62
Potato 44	78.2	-6.9	75.4	10.26	5.90
Potato 45	79.1	-8.1	20.5	15.01	7.25
Potato 46	77.1	19.5	71.3	1.53	6.61
Potato 47	78.2	21.2	21.6	0.17	6.91
Potato 48	74.8	22.5	13.3	7.43	6.48
Potato 49	78.1	-12.0	12.1	24.99	7.22
Potato 50	77.3	32.8	3.8	5.57	7.98
Potato 51	76.3	-18.2	3.3	28.30	6.59
Potato 52	76.6	-45.2	44.5	8.79	6.57
Potato 53	78.2	15.6	45.0	2.93	5.82
Potato 54	77.5	24.4	47.2	-5.53	5.07
Potato 55	76.1	38.6	47.4	-9.20	6.88
Spinach 1	43.2	-33.5	32.2	20.62	4.68
Spinach 2	46.2	4.1	32.9	-11.12	5.18
Spinach 3	42.9	13.9	32.6	-6.86	5.57
Spinach 4	43.1	-34.6	22.8	22.98	4.84
Spinach 5	46.7	-34.4	14.1	20.14	4.11
Spinach 6	46.4	-36.5	43.1	22.10	4.63

Spinach 7	42.8	-25.6	38.5	14.47	4.68
Spinach 8	44.7	-26.5	27.7	20.43	4.41
Spinach 9	44.9	-18.7	41.8	13.63	5.36
Spinach 10	42.2	-17.7	23.2	14.78	5.01
Spinach 11	44.2	-10.0	17.9	9.93	5.49
Spinach 12	45.2	0.3	12.7	0.26	5.92
Spinach 13	46.8	7.8	9.0	1.06	6.09
Spinach 14	46.2	-38.3	24.4	18.92	4.74
Spinach 15	44.9	-41.0	40.4	15.02	5.15
Spinach 16	43.5	-29.2	23.8	15.42	4.79
Spinach 17	45.2	-30.1	41.5	15.09	4.81
Spinach 18	44.1	-24.3	16.0	20.27	4.58
Spinach 19	44.1	-21.9	7.3	23.08	4.20
Spinach 20	45.2	-15.0	-0.4	17.43	4.66
Spinach 21	45.2	-10.3	-11.3	23.47	5.08
Spinach 22	45.6	-25.1	33.3	14.21	5.05
Spinach 23	44.8	-15.1	32.3	13.84	4.51
Spinach 24	45.5	-5.1	33.7	-3.33	5.37
Tomato 1	51.8	53.6	43.2	3.13	5.55
Tomato 2	53.1	55.9	31.8	8.71	6.31
Tomato 3	54.9	55.3	23.2	4.51	7.65
Tomato 4	53.5	55.8	15.2	12.08	6.86
Tomato 5	52.0	53.3	3.7	4.40	6.50
Tomato 6	52.8	53.2	-6.3	4.72	6.78
Tomato 7	52.6	54.6	51.4	0.81	5.26
Tomato 8	53.7	45.7	42.5	3.64	5.45
Tomato 9	53.8	46.0	49.2	7.05	5.06
Tomato 10	53.5	46.8	37.3	3.99	5.11
Tomato 11	54.8	63.4	47.4	-3.65	6.92
Tomato 12	53.1	62.8	38.1	-6.92	6.81
Tomato 13	53.9	37.0	52.8	23.44	4.68
Tomato 14	53.7	37.8	32.1	8.03	5.71
Tomato 15	54.8	70.5	33.8	-3.45	6.38
Tomato 16	52.2	34.7	43.1	1.35	5.92
Tomato 17	53.5	30.1	26.7	-0.36	6.39
Tomato 18	55.0	20.4	22.4	17.28	5.65

Tomato 19	52.5	11.2	18.8	10.21	5.85
Tomato 20	53.4	24.1	42.8	15.77	5.09
Tomato 21	52.2	49.0	34.2	5.97	6.22
Tomato 22	52.5	50.2	51.5	11.17	4.52
Tomato 23	54.7	61.2	34.4	2.71	5.79
Tomato 24	53.1	60.1	49.7	10.19	5.92
Tomato 25	52.4	65.1	25.3	6.43	6.16
Tomato 26	53.9	44.5	25.7	16.79	5.15
Tomato 27	53.3	16.3	43.7	22.56	4.74
Tomato 28	52.6	41.3	18.6	9.14	5.48
Tomato 29	53.5	69.7	16.2	17.36	6.14
Tomato 30	52.5	75.9	8.4	2.21	5.94
Tomato 31	53.4	34.5	10.1	4.09	5.63
Tomato 32	54.9	80.7	1.6	4.26	5.76
Tomato 33	52.9	30.6	0.3	2.90	4.91
Tomato 34	52.8	4.4	41.9	1.84	5.70
Tomato 35	54.4	65.2	43.3	9.00	5.00

Appendix C Average preference ratings for participants in Experiment 3

Color Name	S01		S02		S03		S04		S05		S06		S07		S08		S09		S10	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
DR	-10.10	1.72	89.90	0.86	-77.30	8.19	55.50	8.37	98.60	1.40	85.20	2.20	84.60	2.21	2.40	4.76	83.80	2.79	-34.50	1.98
DO	-2.20	5.43	5.90	2.58	-37.70	9.16	51.40	5.08	-26.60	3.31	0.00	0.00	-1.60	2.07	2.40	1.93	10.20	4.97	-23.10	7.55
DY	-10.70	2.26	83.50	1.82	-89.10	7.47	0.20	2.86	-97.00	3.00	-4.70	4.70	-73.60	4.77	22.00	3.61	52.00	5.61	-30.00	2.39
DH	4.60	6.21	89.40	1.40	-21.10	13.56	62.10	5.32	-38.00	11.64	11.90	5.45	-0.20	4.56	33.30	5.50	51.00	3.78	-13.00	10.03
DG	-9.90	5.97	83.30	2.49	56.70	15.02	41.30	8.10	-79.10	6.67	-21.30	4.61	42.80	4.04	46.90	9.20	55.40	5.40	31.20	2.08
DC	-11.60	4.42	69.20	2.95	67.90	15.05	52.50	6.99	-81.00	4.99	-13.60	4.86	81.60	2.32	55.10	8.46	55.30	4.83	28.10	6.00
DB	-1.40	6.81	61.20	5.24	49.50	14.76	71.60	4.29	-34.80	11.05	62.40	8.75	82.10	3.85	36.00	7.33	62.70	4.79	31.70	3.32
DP	32.70	4.94	74.40	2.51	-6.70	12.89	39.40	6.57	-75.30	4.48	0.00	0.00	-0.40	3.99	33.80	6.02	-26.00	4.18	26.80	7.00
LR	-14.60	2.40	13.80	4.51	41.80	5.75	56.50	7.33	33.00	14.73	1.70	1.70	11.30	2.72	-8.80	3.23	-40.50	5.36	-5.90	10.11
LO	5.30	5.91	6.10	3.64	49.50	5.77	51.90	6.14	-27.10	8.65	-0.70	0.70	1.50	2.40	-19.50	4.77	-47.10	6.34	-16.20	8.87
LY	23.70	2.09	55.90	2.38	37.40	10.73	17.50	7.80	-18.30	9.80	0.00	0.00	10.30	1.92	-34.00	8.90	-36.40	5.84	-21.90	8.60
LH	19.50	3.85	60.00	1.24	65.30	8.13	18.70	6.11	-40.40	6.57	0.00	0.00	6.90	1.72	-10.90	3.90	3.30	5.50	-33.90	2.77
LG	-5.70	5.30	53.70	2.62	88.70	6.11	50.10	6.37	39.30	14.50	0.00	0.00	21.50	3.30	-15.80	5.00	8.30	5.40	30.00	5.69
LC	-13.90	1.20	49.60	4.41	76.80	7.86	64.70	4.60	44.30	7.81	0.00	0.00	29.30	4.32	-13.90	1.59	-15.30	4.03	43.10	1.37

LB	8.10	5.94	58.10	3.82	69.80	11.05	62.90	5.00	57.70	12.07	18.10	2.18	24.50	5.81	-5.90	1.18	12.60	4.92	46.80	2.22
LP	19.50	4.84	48.10	2.71	41.50	16.41	47.80	4.71	-3.90	10.70	0.00	0.00	24.20	4.80	-3.00	2.29	-20.20	7.00	40.80	2.59
MR	-7.00	4.04	29.60	4.34	-17.40	16.59	56.00	6.47	-1.50	10.24	5.40	3.96	26.00	3.99	7.70	1.81	-4.50	8.11	-13.60	8.77
MO	7.20	5.83	7.40	2.99	-26.80	11.15	46.30	4.55	-28.40	6.59	0.00	0.00	-2.60	2.48	4.30	1.78	0.90	6.27	-29.90	5.80
MY	6.80	4.76	13.40	2.49	-5.30	12.70	25.00	6.92	-18.20	6.90	0.00	0.00	-8.60	4.94	3.40	2.53	21.00	4.55	-21.30	7.93
MH	-3.60	6.17	36.40	2.29	92.80	4.56	52.40	7.02	-39.70	8.06	0.00	0.00	-6.70	2.49	-2.70	1.93	29.20	7.47	-28.70	2.42
MG	-14.50	1.47	42.30	4.86	74.00	7.39	62.30	8.55	48.10	10.30	-6.50	4.66	15.00	2.33	-0.20	1.93	17.10	4.21	30.30	7.02
MC	-11.00	4.40	45.20	3.74	92.10	5.38	53.80	7.15	69.10	9.71	16.10	4.88	37.20	4.35	-1.80	1.58	6.40	3.74	38.30	1.83
MB	11.30	5.75	48.70	4.45	59.90	12.97	65.50	5.04	72.30	10.27	39.00	5.01	29.20	3.26	5.40	1.64	20.20	3.99	40.90	2.62
MP	18.80	4.23	47.60	4.52	27.50	13.50	56.70	5.35	49.30	6.31	0.00	0.00	21.00	4.15	19.70	3.78	-28.80	5.80	35.40	2.69
SR	-7.80	5.04	73.50	3.29	-35.70	10.27	27.60	5.10	-37.20	11.91	64.50	3.15	65.30	3.47	-56.80	5.05	-62.70	6.60	-30.40	1.83
SO	24.70	3.14	83.60	3.54	0.00	12.76	-11.00	1.65	-74.00	7.00	2.10	2.10	37.90	4.09	-51.50	7.01	-70.60	9.35	-9.40	10.31
SY	25.80	3.64	29.00	2.82	-1.90	9.27	-10.10	1.64	-69.70	11.54	0.00	0.00	57.70	3.11	-61.70	7.33	-84.10	3.80	-32.30	1.76
SH	-0.80	5.31	75.80	7.67	95.20	4.80	-10.10	4.59	-74.80	7.96	54.00	4.07	50.30	4.03	-18.80	3.91	-14.00	4.81	-25.80	7.16
SG	-8.40	3.92	62.30	3.86	60.20	10.16	2.50	4.40	-20.50	10.90	-47.70	6.81	45.20	5.91	-40.90	3.53	-27.50	3.69	24.30	9.60
SC	-7.00	4.49	21.10	4.17	26.90	10.88	28.80	5.01	45.60	11.02	0.00	0.00	84.40	1.95	-30.10	6.61	-34.80	6.80	37.90	1.59
SB	-9.30	2.53	11.10	3.64	7.50	13.86	6.90	6.48	10.40	13.49	1.40	1.40	69.90	2.54	-34.00	7.43	-35.00	6.86	40.50	1.67
SP	28.90	2.80	42.10	2.39	-11.10	10.90	-8.10	2.20	-63.00	6.50	-2.90	1.95	50.60	3.51	6.70	5.46	-82.20	4.57	39.30	2.17
