Modulation of cognitive processing by semantic congruency: Evidence from the interaction between facial expression and color

(意味的一致による認知処理の変調：表情と顔色の相互作用)

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Doctor of Philosophy (Engineering)

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Abstract（Doctor）

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Approx. 800 words

The face reflects emotional, physical, and other states. In particular, facial expressions and facial colors provide crucial cues for interpreting others' emotions. Facial expressions are observed as shape changes in facial components such as the mouth, eyes, and eyebrows. In contrast, facial color changes are caused by variations in blood flow beneath the skin, which also fluctuate with emotional arousal. For instance, when a person expresses anger, the eyebrows tend to lower, the lower eyelids become tense, and the lips are opened. Simultaneously, physiological arousal increases blood flow, resulting in a reddish facial appearance. Thus, although facial expression and facial color are independent phenomena, they are interrelated, and this relationship affects judgments and social evaluations. Previous studies have reported that reddish facial colors tend to appear angrier and more aggressive, even with the same facial shape. These modulations have often been discussed as arising from semantic congruency between facial expression and color, formed through physiological or associative knowledge. However, most previous studies relied solely on behavioral tasks (response with button judgment or rating), leaving it unclear whether the observed bias effect arises even under unintentional conditions or merely reflects a response bias at the time of judgmental decision. Therefore, this thesis aimed to elucidate whether cognitive modulation based on the semantic congruency between facial expression and color occurs even in the absence of deliberate (arbitrary) response bias, by employing psychophysical and electroencephalographic (EEG) approaches.

In the first study, I focused on memory color, which is formed from objects' color memory acquired through one's own experience, and examined how facial expression affects facial color memory. Two psychophysical tasks (color adjustment task and color selection task) were conducted to calculate and compare the subjective achromatic point for facial image stimuli with different facial expressions (anger, neutral, fear). The results showed that the subjective achromatic points for angry and fearful faces shifted in the opposite color direction compared to neutral faces. These findings suggested that facial color memories or memory colors depend on facial expressions and the facial colors of angry and fearful faces are memorized as higher saturated.

In the second study, to investigate top-down modulation of brain activity, I analyzed the event-related potential (ERP) P3, which reflects selective attention. An oddball task was conducted, wherein participants counted the occurrences of

infrequent target stimuli among facial image stimuli presented at two different frequencies. EEG was recorded throughout the task, and P3 amplitudes were calculated for each combination of facial expression (angry, neutral) and facial color (original, red, green). The results revealed a significant interaction between facial expression and facial color, showing that the P3 amplitudes for red angry faces were higher than those for red neutral faces. This finding suggested that brain activity reflecting selective attention is modulated by the semantic congruency between facial expression and color. In addition, since the interactions between facial expression and color were not observed at earlier ERP stages than the P3, it has been suggested that the semantic congruency between facial expression and color emerges at a later cognitive processing stage rather than at processing stages associated with either facial expression or facial color alone.

In the third study, I extended from static facial color conditions examined in previous research to dynamic conditions involving changes in facial color, and examined how semantic congruency, including contextual information, influences judgmental modulation. Facial expression judgment tasks were conducted using facial stimuli that differed in facial color state, including dynamic and static conditions. The results showed that, regardless of the total perceived amount of color or the presence of dynamic change, faces with a relatively redder final color were more likely to be judged as angry. These findings suggest that the terminal facial color plays a critical role in facial expression recognition.

The results of this study showed that cognitive modulation based on the semantic congruency between angry and red occurs even in the absence of intentional response bias. These findings suggest that knowledge of the semantic congruency between facial expressions and colors influences cognitive processing not as an explicit judgment strategy, but rather as a top-down process that modulates perception and evaluation. Based on these results, this study proposes a model in which knowledge derived from the semantic congruency between facial expressions and colors does not directly modulate responses. Rather, the congruency modulates cognitive processing, and this modulation subsequently manifests as changes in judgments and responses. This model is expected to extend beyond the relationship between facial expressions and colors, offering a broader framework for understanding how knowledge and memory influence human responses and judgments.

Acknowledgments

"Do what you love and success will follow." - Meg Whitman

Loving my research has added color and meaning to my PhD journey.

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My research career began in my third year as a bachelor student. At that time, I had never considered pursuing a doctoral degree; I simply joined a laboratory that I felt suited me, with the sole intention of completing my bachelor's degree. However, through the enthusiastic guidance of my supervisor and senior lab members, I gradually came to appreciate the intellectual excitement of research. By my fourth undergraduate year, I had decided to pursue the path toward a doctoral degree. In the course of my research activities, I am deeply grateful to my cohort members with whom I advanced our respective research projects together. We supported one another, shared both challenges and successes, and spent truly irreplaceable time together. Beyond research activities, I also enjoyed sharing my personal hobby of coffee within the laboratory, occasionally serving coffee that I brewed myself to lab members. In the evenings, not only current members but also alumni of the laboratory gathered to enjoy online games together. Being surrounded by such supportive people and a welcoming environment allowed me to proceed through my academic journey without losing my peace of mind, for which I am sincerely thankful. It is precisely because I was able to conduct my research in such a fortunate and supportive environment that I have been able to continue my research with genuine enthusiasm and enjoyment. I would also like to express my sincere gratitude to the editors and reviewers who carefully evaluated my research activities and recognized it as worthy of publication in international academic journals.

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Contents

List of Figures

List of Tables

1 | Introduction

1.1 Face

Although the face is a sensory organ common to many living species and merely one among numerous visual objects, it conveys socially significant meaning for humans. We can derive a diverse array of information from the face, including cues to individual identity, emotional states expressed through facial movements, a person's health condition through facial color and other such information (Bruce and Young, 1986).

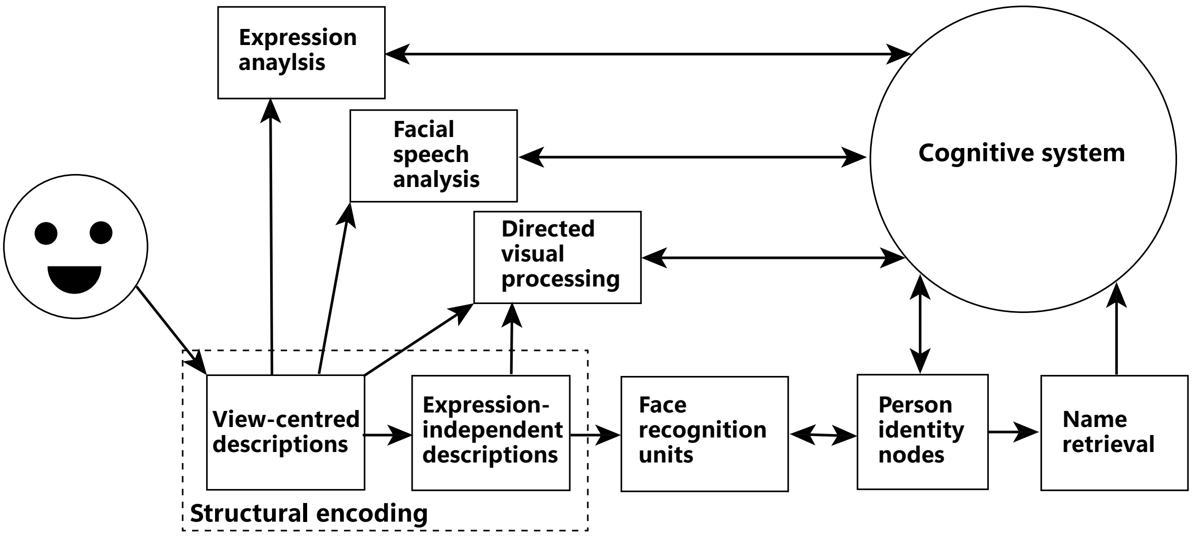

Fig. 1.1.1: Cognitive model of face perception by Bruce and Young (1986)

This thesis examines the perception of faces, focusing particularly on how interaction between facial expressions and facial colors modulates cognitive processing.

1.2 Face perception

Face recognition begins with configural processing, in which the spatial arrangement of facial features such as the eyes, nose, and mouth allows the detection of a face. The configuration and subtle variations of these features not only provide essential information for distinguishing individual identities but also serve as important cues for judging facial expressions (Beaudry et al., 2014; Benitez-Quiroz et al., 2018; Sadr et al., 2003; Wegrzyn et al., 2017). For instance, angry expressions are often described by contracted or lowered eyebrows, widely opened eyes with tensed lower eyelids, and mouth movements characterized by the upper lip being raised and the lower lip pulled downward, exposing the teeth and stretching the corners of the mouth (Kohler et al., 2004).

In addition to the structural configuration of the face, facial color constitutes an important source of information for evaluating an individual's health state and social attributes (Han et al., 2018; Thorstenson et al., 2019; Thorstenson and Pazda, 2021; Lu et al., 2022). For instance, a greenish facial color tends to decrease perceived health and attractiveness, whereas reddish and yellowish colors are associated with higher evaluations of them (Thorstenson et al., 2019; Thorstenson and Pazda, 2021).

1.3 Relationship between emotion and color

Facial expressions and facial colors act as independent factors, yet they are closely interrelated. Facial color is dependent on blood flow, which is known to be modulated by arousal resulting from emotional fluctuations (Edwards and Duntley, 1939; Kikuchi et al., 2015; Zonios et al., 2001; Kreibig, 2010). Facial color reddens when vascular dilation and blood flow increase markedly, as observed in anger, whereas a reduction in facial blood volume leads to a pale or bluish complexion (Drummond, 1997a, 1999; Drummond et al., 2001).

The association between emotions and facial color is reflected not only in physiological responses but also in semantic association and subjective evaluations (Drummond, 1997b; Takahashi and Kawabata, 2018; Jonauskaite et al., 2019, 2020; Thorstenson et al., 2018). For example, it has been reported that reddish colors are significantly more likely to be chosen as those associated with anger, whereas bluish colors tend to be selected as those representing sadness (Takahashi and Kawabata, 2018; Thorstenson et al., 2018). In particular, the association between anger and red appears to be a cross-culturally consistent relationship (Jonauskaite et al., 2020).

Beyond a simple associative relationship, the relationship between emotions and color also influences human recognition of facial expressions and social evaluations (Nakajima et al., 2017; Minami et al., 2018; Peromaa and Olkkonen, 2019; Qin, 2021; Kato et al., 2022; Takei and Imaizumi, 2022; Thorstenson and Pazda, 2021; Thorstenson et al., 2021, 2022; Nguyen et al., 2023). Even when the facial configuration remains constant (i.e., same facial shape), increasing the redness of the face or its background has been reported to shift emotion recognition responses toward anger (Nakajima et al., 2017; Minami et al., 2018; Peromaa and Olkkonen, 2019). Furthermore, reddening an angry face enhances the perceived emotion intensity, as well as the rating for aggressiveness, dominance, and other related evaluations (Thorstenson and Pazda, 2021; Thorstenson et al., 2022).

1.4 Background and Aim

Across numerous studies, alterations in facial expression and social evaluation judgments induced by facial color (see Section 1.3) have been discussed as reflecting top-down processing arising from congruency with physiological factors, such as increases in facial blood flow, as well as semantic associations, including the link between anger and red. However, most previous studies relied on only behavioral tasks (response with button judgment or rating). Therefore, the unintentional responses have not been investigated, and it remains unclear how the semantic congruency between facial expression and color modulates cognitive processing stages and memory functions. Thus, it could not be entirely ruled out that color information may directly bias responses even when facial appearance did not lead to differences in judgment and rating. For instance, a face that does not objectively appear angry might nonetheless be judged (or reported) as angry simply because “the facial color is red,” and evaluation scores could be enhanced for reddish faces despite no difference being observed across other color conditions.

To examine this concern, this thesis investigated whether response activity modulation by the semantic congruency between facial expression and color occurs even in situations where intentional response biases are absent. Therefore, this study aimed to clarify whether the observed judgment modulations in previous studies are attributable to deliberate (arbitrary) response biases (i.e., they emerge solely at the time of responding). In other words, the aim of this study is to determine whether knowledge is merely employed as a judgmental strategy, or whether expectations regarding the congruency between facial expressions and colors actively modulate perceptual representations themselves.

1.5 Research question

In this thesis, the following research question was investigated according to Approaches 1 and 2. Furthermore, by conducting additional investigations through Approach 3, the present study aimed to extend existing knowledge of judgment modulation arising from the interaction between facial expression and facial color.

Research question: Does semantic congruency between facial expression and color modulate not only behavioral responses (i.e., stages affected by intentional bias) but also responses that occur under unintentional bias conditions? For example, is modulation driven by the expectation of semantic congruency between facial expression and color also observed in semantic memory and in brain activity associated with top-down cognitive processing?

Approach 1: Experiential memory (memory color of face / facial expression)

Approach 2: Selective attention and its brain activity (Event-related potential: ERP P3)

Approach 3: The effect of dynamic facial color change direction (facial color change context)

Assuming that the bias effect induced by the semantic congruency between facial expression and color extends to unintentional cognitive processing, it was hypothesized that the memorized facial color would differ across facial expressions (Approach 1), and that modulations of top-down processing, such as selective attention and its related brain activity, would be observed depending on the specific combination of facial expression and color (Approach 2). Furthermore, if the expectation of semantic congruency plays an important role in human responses, it was also hypothesized that the effect of semantic congruency between facial expression and color would become more pronounced in the presence of dynamic changes, given that dynamic change factors are known to facilitate cognitive processing (Approach 3).

1.6 Structure of thesis

Figure 1.6.1 exhibits an outline of this thesis, comprising six chapters. Related studies on the associations between face and facial color, memory color, and relationship between face and Electroencephalogram (EEG) in the main study are mentioned in Chapter 2. In this thesis, I investigated whether the modulation driven by semantic congruency between facial expression and color occur at cognitive processing states under unintentional bias conditions. Chapter 3 focused on examining the effect of facial expressions on facial color memory based on the memory color effect. In Chapter 4, the influence of the semantic congruency between facial expressions and colors on brain activity was explored through EEG. In addition, Chapter 5 examined the extension of existing knowledge regarding judgment modulation by the semantic congruency between facial expressions and colors, utilizing dynamic facial color change information. Finally, the overall summary of the studies and answers to the research question, along with the proposed model, are mentioned in Chapter 6.

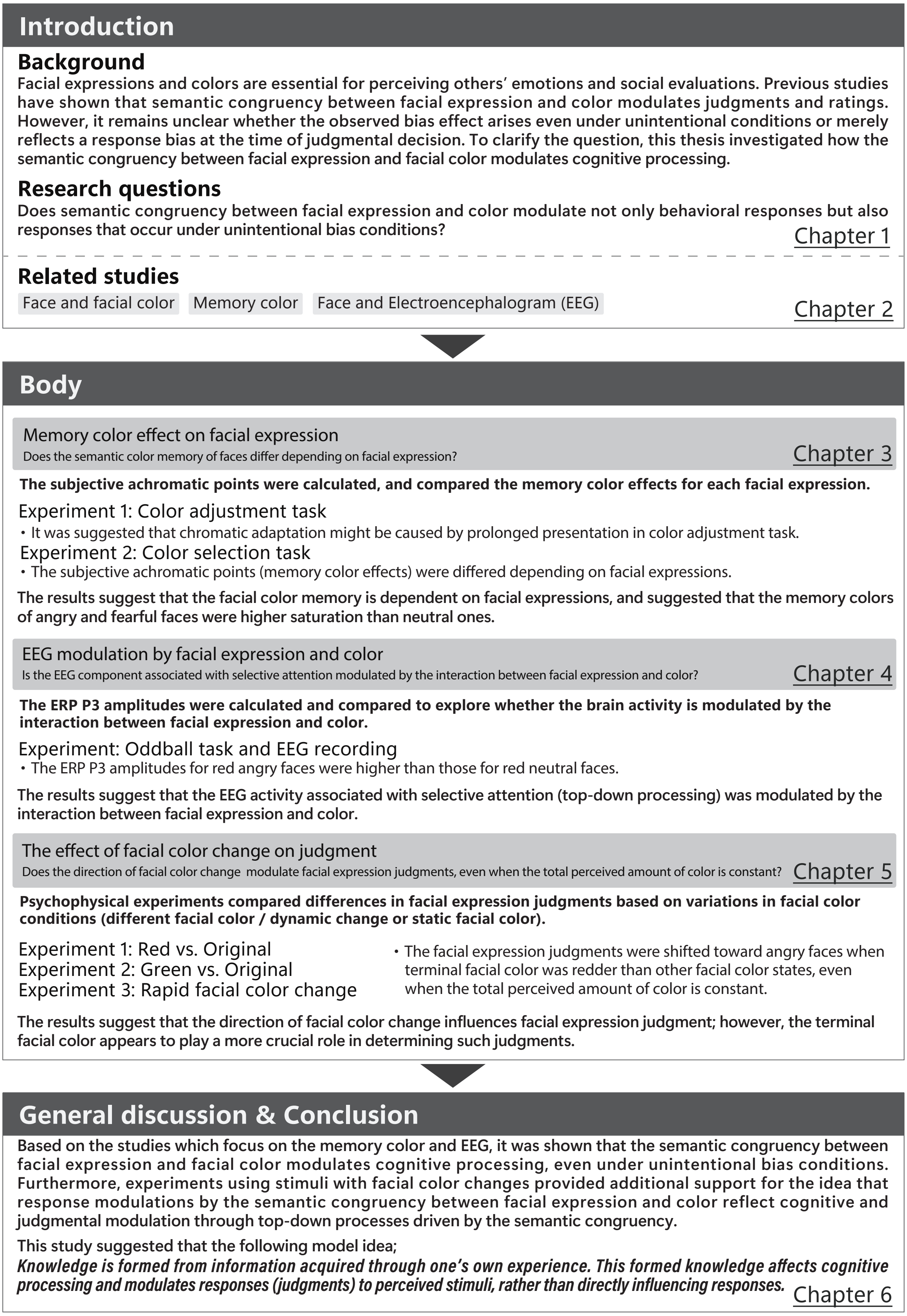

Fig. 1.6.1: Thesis structure

2 Related studies

2.1 Face and facial color

2.1.1 Facial color and physiological findings

The facial color has one of the important roles to judge human health and emotional state (Drummond et al., 2001; Kreibig, 2010). Facial colors stem from the inherent hues of substances such as hemoglobin and melanin, which are included in blood flow, and the amount of hemoglobin and melanin on the face is also affected by emotion (Edwards and Duntley, 1939; Kikuchi et al., 2015; Zonios et al., 2001; Kreibig, 2010). For example, physiological responses such as heart rate, blood pressure, and skin temperature change in relation to emotional states (Kreibig, 2010). Moreover, it has been also reported that facial blood flow increases when people express anger, leading to facial redness (Drummond et al., 2001).

2.1.2 Facial expression recognition

Facial color is one of the factors used to judge facial expressions. The facial color may serve as an independent cue from facial musculature in emotion perception, contributing to the interpretation of emotional expressions (Benitez-Quiroz et al., 2018), and influences the recognition of facial expressions (Nakajima et al., 2017; Minami et al., 2018; Peromaa and Olkkonen, 2019; Qin, 2021; Takei and Imaizumi, 2022; Thorstenson and Pazda, 2021; Thorstenson et al., 2021; Nguyen et al., 2023). In the recognition of facial expressions, a reddish face is more likely to be perceived as angry faces even if the shape of the face remains the same (Nakajima et al., 2017). Nakajima et al. (2017) and Minami et al. (2018) reported that, when participants judge the facial expressions of images of faces morphing from fearful to angry, reddish faces were more likely to be perceived as angry and to be judged as angry faces, even at the same morphing level. In particular, reddish faces have been reported to have a slight influence on the judgment of whether a face is angry, even under strict conditions that control for facial color changes and the number of emotions and colors (Peromaa and Olkkonen, 2019). From a physiological perspective, it has been also reported that facial stimuli with increased redness, which is associated with hemoglobin concentration, enhanced the perception of angry faces (Kato et al., 2022).

2.1.3 Emotion intensity and social evaluation

The relationship between facial expression and color affects the emotion intensity and social characteristics (Thorstenson and Pazda, 2021; Thorstenson et al., 2022). For example, reddish angry faces increase the perception of emotional intensity, aggression and dominance and so on. In contrast, it has been also reported that the greenish angry faces decrease these perceptions (Thorstenson et al., 2022; Thorstenson and Pazda, 2021). In addition, it has been also reported that the reddish facial color increased the friendliness ratings, even if the happy expression was implicit (Nguyen et al., 2023).

2.1.4 Facial color perception / memory

Although facial color has been shown to influence the perception of facial expressions, there is also evidence that facial expressions affect perceived facial color. The criteria used to evaluate human complexion are believed to rely on both the inherent skin color and the conditions that humans typically remember (Hasantash et al., 2019; Shimakura and Sakata, 2022). The relationship between facial expression and color is known to influence color memory of face. For example, Thorstenson et al. (2021) conducted a facial color recall task after presenting facial expression stimuli. Consequently, in the recall task, faces with higher redness and yellowness (CIE a*+, b*+) were selected significantly more often than the faces that had actually been presented, indicating that the remembered facial color was biased toward red and yellow. They also reported that blushing emotion (e.g., anger and happiness) was recalled more vividly than paling (e.g., fear and sadness) for the reddish-yellowish components of facial color.

2.2 Memory color (Luo, 2016)

Definition A memory color is the typical color of an object that an observer acquires through their experience with that object.

A memory color refers to an observer's stored knowledge of the typical color associated with a familiar object. The typicality of this memorized color suggests that the observer regards it as representative, or "canonical," of the range of colors in which that object usually appears. Consequently, the memory color shapes the observer's expectation regarding the object's color based on prior visual and conceptual experience. For example, it is generally acknowledged that the color yellow is typically associated with a ripe banana. This knowledge about typical colors becomes a memory color.

Memory colors are thought to exert a direct influence on the perceived color of objects (memory color effect). In addition, memory colors have been shown to influence color memory; for instance, when observers recall the actual color of a diagnostic object, the remembered color tends to be biased toward the object's memory color.

2.2.1 Memory color effect

According to classical idea of a "memory color effect," memory colors have a direct effect on how the actual color of objects is perceived. The memory color effect demonstrates that the perceived color of an object depends on both the properties of the object and the observer's prior experiences and knowledge.

Color adjustment task (Hansen et al., 2006; Olkkonen et al., 2008)

One common method for measuring the memory color effect is a color adjustment task. For example, Hansen et al. (2006) and Olkkonen et al. (2008) conducted a color adjustment task in which the color of fruit and vegetable stimuli presented on display was adjusted to an achromatic or typical color. The results showed that the achromatic adjustment points of the stimulus shifted in the opposite color direction to the typical color (adjustment point of the typical color). They reported that the color of the object memorized by the participant, and the fruit that was physically achromatic in the color space appeared to be colored in the typical color.

Color selection task (Witzel, 2016)

Another approach for assessing the memory color effect involves a color selection task. Witzel (2016) conducted color selection task in which participants were asked to evaluate the colors of two stimuli. The results indicated that, even without strict color calibration, participants were significantly more likely to select a bluish banana over a pure gray banana. And the study suggested that color perception of object changes because of the memory color effect.

2.3 Face and Electroencephalogram (EEG)

EEG is a record of electrical activity generated by the brain using electrodes placed on the scalp. EEG elicited in associated with specific perceptual or cognitive processing events are referred to as event-related potentials (ERPs). Furthermore, it has been reported that several ERP components, including P1, N170, and P3 (Figure 2.3.1), are associated with the processing of faces.

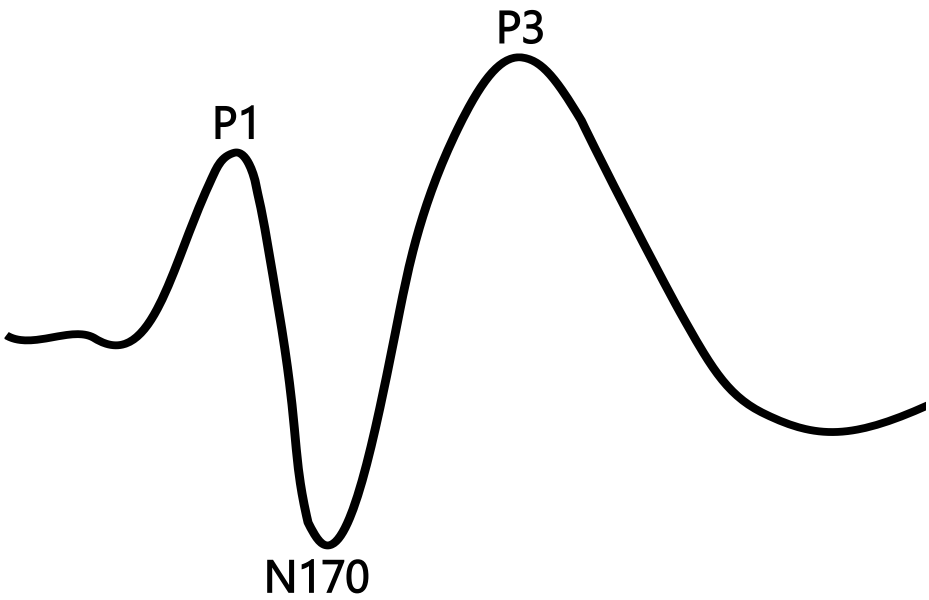

Fig. 2.3.1: Schematic illustration of ERPs

2.3.1 P1

P1 is a positive ERP component that is observed ∼100 ms after a presented stimulus in the occipital region and reflects the initial visual processing (Hillyard and Anllo-Vento, 1998; Colombatto and McCarthy, 2017). The P1 amplitude is thought to reflect the perception of low-level visual cues during early face processing, and it has been reported that P1 amplitudes for faces are larger than those for non-face stimuli (Rossion and Caharel, 2011; Herrmann et al., 2005). However, previous studies have indicated that facial expression factors have a limited impact on the modulation of the P1 component (Schindler and Bublatzky, 2020).

2.3.2 N170

N170 is a negative ERP component that occurs ∼170 ms after stimulus presentation in the left and right posterior temporal regions and is sensitive to facial stimuli (Bentin et al., 1996). Additionally, N170 is modulated by facial expression and facial color (Minami et al., 2011; Nakajima et al., 2012; Hinojosa et al., 2015). It has been reported that N170 amplitudes are larger in response to emotional expressions, such as angry faces, compared with neutral faces (Schindler and Bublatzky, 2020; Hinojosa et al., 2015). In addition, Minami et al. (2011) and Nakajima et al. (2012) have suggested that N170 amplitudes to facial color reflect the unnaturalness of the face's coloration.

2.3.3 P3

P3 is an ERP component that occurs ∼300–500 ms after a presented stimulus at the parietal lobe as the third positive deflection. ERP P3 is one of the EEG components associated with top-down processing such as selective attention. With respect to the relationship between facial expressions and P3 amplitudes, previous studies have shown that attention to angry or fearful faces increases the P3 amplitude (Rossignol et al., 2005; Kiss and Eimer, 2008; Chai et al., 2012; Lin et al., 2020). Moreover, the P3 component reflects feedback from brain regions involved in memory functions (Polich, 2007; Klimesch et al., 2000; Huang et al., 2015).

Oddball task

The oddball paradigm is one of the tasks that induces a large P3 amplitude. In the oddball task, participants count how often a low-frequency or specified stimulus (target stimuli) appears among stimuli at other frequencies (standard stimuli). Because target stimuli elicit strong selective attention, low-frequency stimuli evoke large P3 amplitudes during the oddball task. In addition, Klimesch et al. (2000) reported that larger P3 amplitudes have been observed when previously learned words were correctly recalled than when new words were presented in oddball task (Klimesch et al., 2000).

3 Memory color effect on facial expression

This chapter focused on memory color and examined whether the semantic congruency between facial expressions and colors gives rise to perceptual modulation driven by semantic memory. This study investigated whether the memory color of faces varies depending on facial expression.

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3.1 Introduction

Facial color is one of the factors used to judge facial expressions. A reddish face is more likely to be perceived as an angry face and is interpreted as having a higher emotional intensity of anger (Kato et al., 2022; Minami et al., 2018; Nakajima et al., 2017; Thorstenson et al., 2019, 2021). Thus, do humans really remember the color of angry faces as being redder than neutral faces?

The criteria for judging human complexion are thought to be based on skin color and conditions that humans typically remember (Hasantash et al., 2019; Shimakura and Sakata, 2022). The relationship between color and emotion is known to influence human facial color memory. For example, Thorstenson et al. (2021) conducted a facial color recall task after presenting facial expression stimuli. Consequently, the redder and yellower (CIE a*, b*) face was chosen in the recall task significantly more often than the face that was actually displayed, suggesting that the remembered facial color was biased toward red and yellow. They also noted that blushing (e.g., anger) was recalled more vividly than paling (e.g., fear) for the red-yellow component of facial color. Thus, at least in temporal memory during the experimental period, the facial color components were amplified in memory, and their magnitude changed depending on facial expression.

However, previous studies have focused only on temporary color memories, and no study has yet investigated whether such memory biases are empirically driven in daily life (e.g., Thorstenson et al., 2021). If facial expressions bias temporary color memory retention, a similar bias is likely to appear in long-term memory. Therefore, humans may remember the facial color of certain expressions more vividly in the long term, forming social and experiential memories related to their daily lives. Thus, I focused on the color of objects related to experiential, long-term memory from the perspective of color memory.

Memory color is defined as the typical color of an object that a human acquires through their experience (Witzel and Gegenfurtner, 2013). For example, most people recognize that the color of a ripe banana is yellow; this knowledge of typical colors is the memory color. Memory color influences human color perception (Hansen et al., 2006; Olkkonen et al., 2008). Hansen et al. (2006) conducted a color adjustment experiment in which the color of fruit and vegetable stimuli presented on display was adjusted to an achromatic or typical color. They found that the achromatic adjustment points of the stimulus shifted in the opposite color direction to the typical color, which was the color of the object memorized by the participant, and the fruit that was physically achromatic in the color space appeared to be colored in the typical color (Olkkonen et al., 2008). As another example of investigating the effect of memory color, Witzel (2016) conducted online experiments in which participants were asked to rate the colors of two stimuli. The results showed that even in the absence of strict color calibration, participants were significantly more likely to select a bluish banana over a pure gray banana, suggesting robust color perception changes because of the memory color effect (Witzel, 2016).

From these previous studies, I combined the idea that the memory color paradigm could be used to reveal memorized colors associated with facial expressions through long-term memory.

Therefore, this study aimed to clarify the dependence of facial color memory on facial expressions, specifically focusing on the effect of memory color. The relationship between facial color and facial expression raises the following research question: Do humans remember angry faces as reddish rather than neutral? Due to objects like bananas, which have a typical color, the achromatic state appears tinted in memory color, and the subjective achromatic point shifts in the opposite color direction. For instance, if an observer memorizes an angry face as more reddish-yellowish than neutral in one's life experience, the red and yellow components of the memory color for angry faces will have higher saturation than for neutral faces. Thus, I hypothesized that the subjective achromatic point is more likely to shift toward the opposite color direction of the facial tone. In other words, we can anticipate evaluating the differences in the memory color of each facial expression based on the magnitude of the shift from the participants' subjective achromatic point of each facial expression when the memory color of a neutral face is used as a reference. Building upon previous research (Hansen et al., 2006; Olkkonen et al., 2008), Experiment 1 attempted to estimate the effect of memory color using an adjustment task. In Experiment 2, I estimated the effect of memory color using the constant method, referencing previous research (Nakajima et al., 2017).

3.2 Color adjustment task (Experiment 1)

First, I conducted a color adjustment task to estimate differences in memory color from the subjective achromatic point of each facial expression, following the methods outlined by Hansen et al. (2006) and Olkkonen et al. (2008).

3.2.1 Materials and methods

Participants

The number of participants was determined to be 15 based on a previous study (Olkkonen et al., 2008). Owing to the experiment's duration, I was able to recruit 13 students from Toyohashi University of Technology (two women, mean age 22.46 ± 0.93) to participate. I used the Ishihara Color Vision Test Chart Ⅱ Concise Version 14 Table, provided by the Public Interest Incorporated Foundation Isshinkai, Handaya Co., Ltd, Tokyo, Japan. All participants correctly matched the prepared answers. They were provided with an introduction to the experiment, excluding the study's hypothesis (see Procedure and task), and gave informed consent to participate. This experiment was conducted with the approval of the Ethics Review Committee for Research Involving Human Subjects at Toyohashi University of Technology.

Stimuli and apparatus

Twelve facial images were prepared as stimuli (Figure 3.2.1A), which were obtained from angry, neutral, and fearful faces of four Japanese individuals (two women and two men) from the ATR Facial Expression Image Database (ATR-Promotions, Kyoto, Japan, `https://www.atr-p.com/products/`

`face-db.html`). Previous research (Nakajima et al., 2017) compared anger and fear using the same database of facial images. I used angry and fearful faces to compare with the baseline (neutral face) because the color directions associated with angry and fearful faces were different (Thorstenson et al., 2018). The hair, ears, and neck in the images were removed in an oval shape using Photoshop (Adobe Systems Inc., San Jose, CA, USA). Additionally, a banana image was used as a control condition, as in the memory color measurement experiment (Nakajima et al., 2010). All images were adjusted to maintain an average image luminance of $16.9\,\mathrm{cd/m^2}$ using "SHINE_color," a MATLAB 2021a toolbox (Mathworks, Natick, USA) (Ben, 2021; Willenbockel et al., 2010). The image dimensions were $4.3\,\mathrm{deg} \times 5.7\,\mathrm{deg}$. The mean and standard deviation of CIE L*a*b* values in the original faces were 47.63 ± 0.05 in L*, 7.57 ± 0.10 in a*, and 22.4 ± 0.12 in b*, respectively (See Figure 3.2.1B). The background color was gray, with a luminance identical to the average image luminance ($[x, y] = [0.31, 0.33], Y = 16.9\,\mathrm{cd/m^2}$).

The experiment was conducted in a booth, with stimuli presented on a monitor (EIZO CG319X; Eizo Corporation, Hakusan, Ishikawa, Japan; Resolution: 1920×1080; frame rate: $60\,\mathrm{Hz}$) set at $200\,\mathrm{lux}$ in front of the participant's chair. The monitor was calibrated using a spectroradiometer (SR-3AR; Topcon, Tokyo, Japan), with its white-point chromaticity was $x = 0.31$, $y = 0.33$, $Y = 99.7\,\mathrm{cd/m^2}$. The participants were seated and performed the task while keeping their heads on a chin rest positioned $70\,\mathrm{cm}$ away from the display. Psychotoolbox 3.0.17 served as the experimental control software (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

Procedure

Figure 3.2.2 depicts a summary of the experimental procedure. Following a $0.5\,\mathrm{s}$ inter-stimulus interval, participants adjusted the color of the presented stimulus to achromatic using a numeric keypad. They were instructed as follows: "Please adjust the color of the presented image stimulus to achromatic using two buttons. Each button corresponds to a typical color and its opposite color direction." I used the CIE L*a*b* space, which has been used in several prior studies to render faces reddish by modulating the a* value for controlling the colors of the stimuli (Minami et al., 2018; Nakajima et al., 2017; Thorstenson et al., 2018; Thorstenson and Pazda, 2021). Additionally, it was possible to alter the color while maintaining lightness. The conversion from RGB values to L*a*b* values in MATLAB was based on the XYZ values of D65, because the display was calibrated close to D65. The colors of the stimuli varied linearly, connecting the actual image color point in the L*a*b* space to the achromatic point

Participants manipulated the stimulus color in the original-opposite direction (Figure 3.2.1B). Since

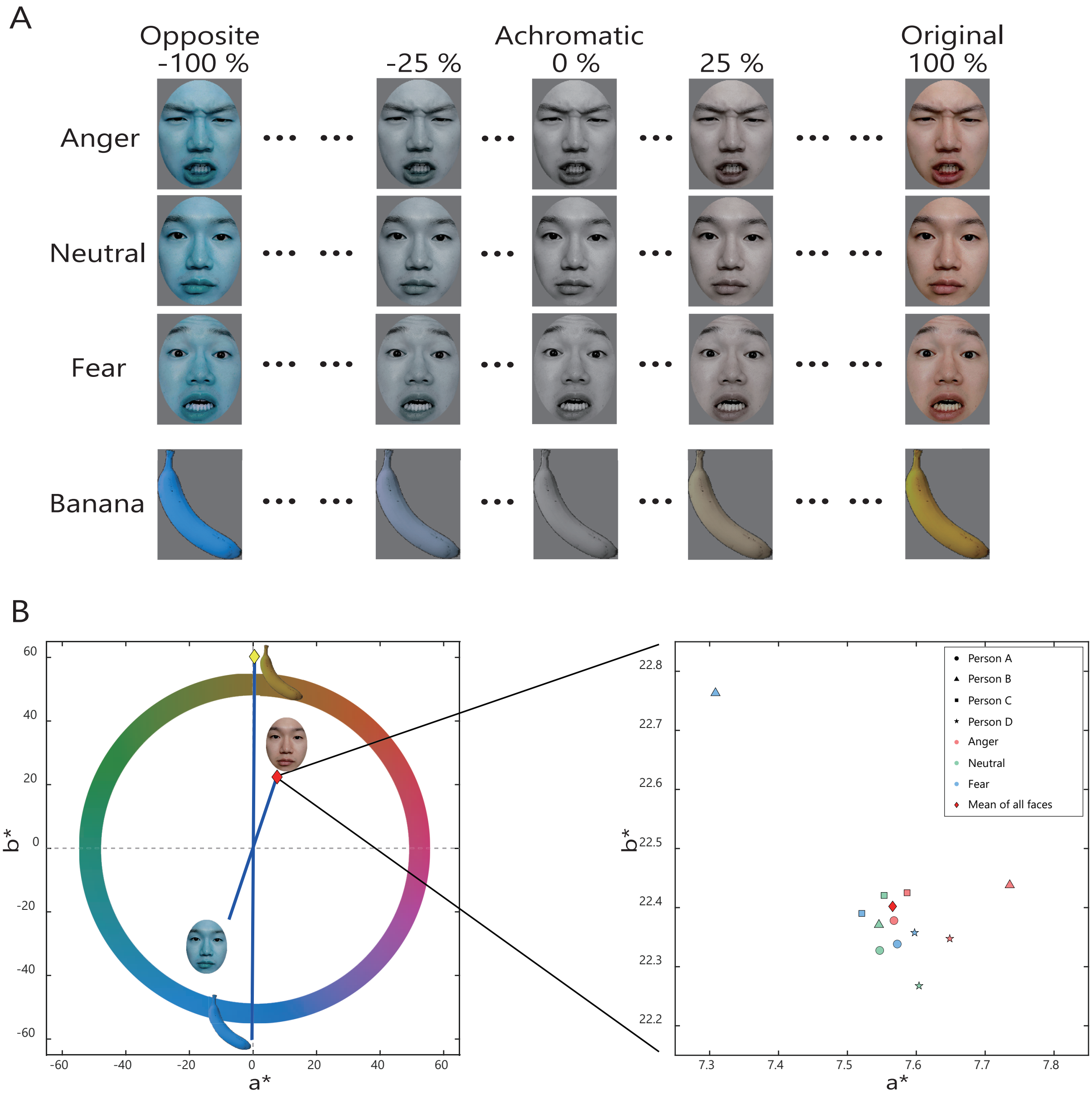

Fig. 3.2.1: Experimental stimuli (Exp.1)

(A) Examples of the color state for each image condition. **(B)** The mean a*-b* values of the image stimuli. A red diamond represents the mean of all face image stimuli, and a yellow diamond represents the mean of the banana stimulus. Blue lines denote the averages of color change axes for the face and banana stimuli. Individual points on the right side represent each face image stimulus, including three facial expressions and four individuals. The red diamond corresponds to the left side. The faces in the figure are one of the author's faces (Y.H.), which was not used in the experiment.

Fig. 3.2.2: Experimental procedure (Exp.1)

Procedure of Experiment 1. Notably, the ratio of the screen to the stimulus depicted in this figure differs from the actual ratio.

the image information varies depending on each image, the original-opposite color directions were set accordingly. The two buttons on the numeric keypad corresponded to the color directions of the original and opposite colors, respectively, and one press changed the state to $\alpha = \tan\frac{\pi}{4}\beta$ %, where α represented the state of the stimulus color and β was a variable with increments or decrements of 1 %. When the achromatic color was 0 %, the original color was 100 %, and the opposite color was -100 %; thus the amount of color change by the numeric keypad was nonlinear. This nonlinear manipulation function was determined by a preliminary experiment in which the participants found it easy to operate.

When the participant pressed the button indicating they had finished adjusting, a Mondrian noise image (width $13.8\,\mathrm{deg}$ $\times$ height $13.8\,\mathrm{deg}$) was presented for $1.0\,\mathrm{s}$ to eliminate the image aftereffects. The stimuli were presented five times per image in a random order, beginning with a randomly selected initial color near achromatic ($\beta = -10 - 10$ %). There were 65 trials in total (13 images × 5 repetitions). The participant was allowed to take a break every 13 trials, and the duration of the break was left to the participant's discretion

Data analysis

The achromatic adjustment values judged by the participants as achromatic were averaged for each condition (anger, neutral, fear, and banana). Then, I calculated the degree to which the achromatic adjustment point shifted as a percentage of the original/opposite color for each condition across all participants.I conducted a Friedman test on the facial expression condition using R because the normality of the data was not confirmed by the Shapiro-Wilk test. Additionally, for the banana condition, since the normality of the data was confirmed by the Shapiro-Wilk test, a one-sample t-test was performed to examine whether I replicated the effect of memory color, as suggested by a previous study (Olkkonen et al., 2008).

3.2.2 Results

Facial expressions

Figure 3.2.3A displays the adjusted results for all facial expressions. The average adjusted points and their standard errors were -0.18 ± 0.34, 0.04 ± 0.42, -0.54 ± 0.37 for anger, neutral, and fear conditions, respectively. There was no significant main effect of facial expression condition ($\chi^2 = 0.154$, $p = 0.926$). This suggests that the memory color of a face does not depend on the facial expression. One possible factor was the prolonged presentation of the image stimulus. The adjustment task took an average of 9.39 seconds (with a maximum of $48.80\,\text{s}$), suggesting that chromatic adaptation may have extended the achromatic perceptual range (Oleari, 2016). In addition, the correlations in each facial expression condition were calculated from the achromatic adjusted value and response times of all trials. As a result, weak positive correlations were found between the adjustment value and reaction time for the facial expression conditions (Anger: $n = 260$, $\rho = 0.190$, $adj.p < 0.001$; Neutral: $n = 260$, $\rho = 0.155$, $adj.p < 0.01$; Fear: $n = 260$, $\rho = 0.289$, $adj.p < 0.001$). The longer the task time, the greater the adjustment value tended to be in the original color direction. Furthermore, humans are thought to be more sensitive to color changes in faces than in non-faces. Humans perceive a larger color difference in faces than in non-faces, even with the same amount of color differences (Thorstenson et al., 2017). Therefore a better method might involve calculating the memory color effect in faces from the observer's color discrimination to several facial color stimuli rather than from a procedure in which observers can perceive continuous color changes.

Banana

Contrary to this, in Figure 3.2.3B, the achromatic adjustment ratio of the banana (-1.16 ± 0.21) significantly shifted in the opposite color direction ($t\left(12\right) = -5.561$, $p < 0.002$, Cohen's $d = -1.542$). This finding suggests that the banana is shifted more in the opposite color direction than the neutral gray and supports previous studies reporting that the achromatic adjustment point of bananas was farther than the subjective achromatic adjustment point (defined as the achromatic adjustment point of a control image such as a noise disk) in the opposite color direction (Han et al., 2018; Olkkonen et al., 2008). My results are similar to those of previous research, where bananas with slightly opposite colors (slightly bluish) were judged to be grayer than bananas with the same chromaticity as the background color (Witzel, 2016).

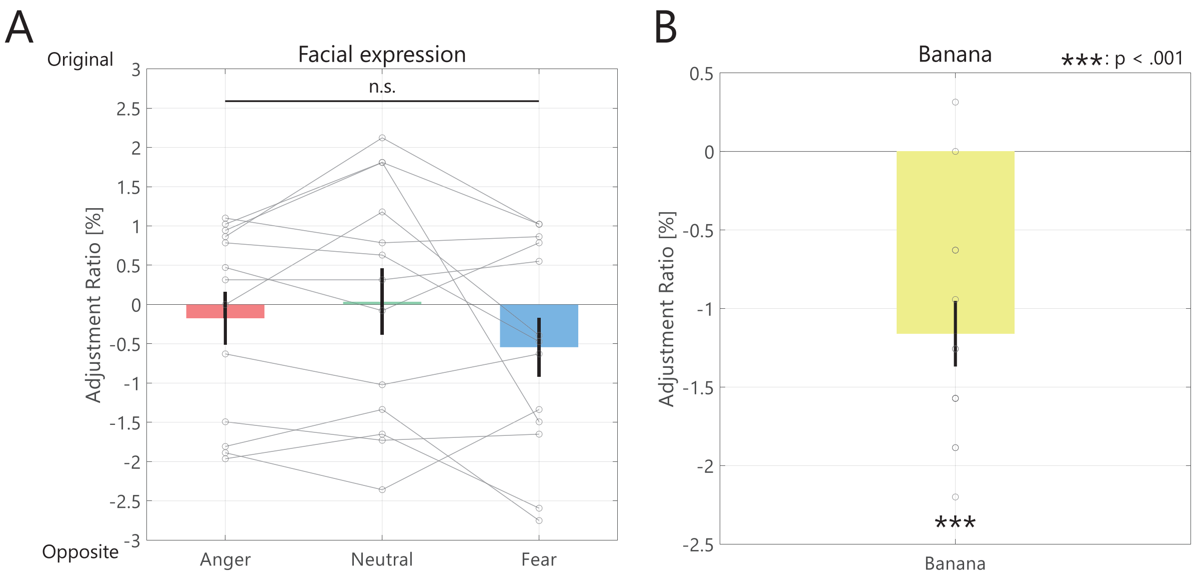

Fig. 3.2.3: Results (Exp.1)

Results of Experiment 1. Participants' mean of the achromatic adjustment point (**A**, Facial expression condition; **B**, Banana condition). Each gray points show individual data. Error bars represent the standard error of the mean.

3.2.3 Discussion

In summary, in Experiment 1, I conducted a color-adjustment task in which participants adjusted the stimulus color to make it achromatic. However, the results showed no significant differences in the memory color effect of facial expressions. A potential reason for these findings could be that chromatic adaptation may be caused by prolonged presentation, and humans are thought to be more sensitive to color changes in faces. Thus, Experiment 2 investigated differences in memory color effects between facial expressions based on a task in which the presentation time was shortened and the colors of stimuli were selected from two color choices. I refer to the simpler color selection task by Witzel (2016).

3.3 Color selection task (Experiment 2)

In the hypothesis, if the memory of facial color is affected by facial expression color (e.g., anger being red, fear being blue), the subjective achromatic point of the face would vary depending on the facial expression. However, the results of Experiment 1 showed no significant difference in subjective achromatic points between facial expressions. A possible explanation for these results could be the occurrence of chromatic adaptation, which may have expanded the range of achromatic perception, resulting in large individual differences in subjective achromatic points in the facial expression condition. Therefore, in Experiment 2, a color selection task was conducted using a “Yes/No task” in which participants selected the briefly presented image stimulus that they thought appeared to be a certain color. This method was used to calculate the subjective achromatic point and to investigate differences in facial color memory between facial expressions.

3.3.1 Materials and methods

Participants

Twenty-three students (four women, mean age 20.87 ± 1.32) participated in this study at Toyohashi University of Technology. The sample size was calculated using PANGEA (Westfall et al., 2014) with an effect size of $d = 0.5$, $power = 0.8$, and $\alpha = 0.05$. As in Experiment 1, all participants were fully informed about the experiment and consented to participate; only participants who passed the color vision test were recruited.

Stimuli and apparatus

The facial expression stimuli and their color change between the point of the actual image color and its achromatic counterpart in L*a*b* (original-opposite axis) were consistent with Experiment 1. Additionally, to confirm whether the angry face simply appears reddish visually rather than as a result of a memory color effect, I included the axes of a* (red-green) and b* (yellow-blue) in the CIE L*a*b* space as control conditions (see Figure 3.3.1). I used these conditions to confirm whether the achromatic angry and fearful faces simply appear reddish/yellowish and greenish/blueish visually, respectively, rather than exhibiting a memory color effect. I hypothesized that the subjective achromatic points of faces are not different between facial expressions in a* and b* axis conditions because the angry and fearful faces did not affect facial color judgment in previous research (Nakajima et al., 2017). In the original-opposite condition, the face stimuli changed color within a range of -4.5 % to 4.5 % in 1.5 % increments (seven steps), with the defined states being achromatic: 0 %, original: 100 %, and opposite color: -100 %. Moreover, in a* and b* conditions, the face stimuli changed color within a range of -1.5 unit to 1.5 in 0.5 increments (seven steps) for each condition. These ranges and step widths were determined based on preliminary experiments.

The experimental environment was the same as that of Experiment 1.

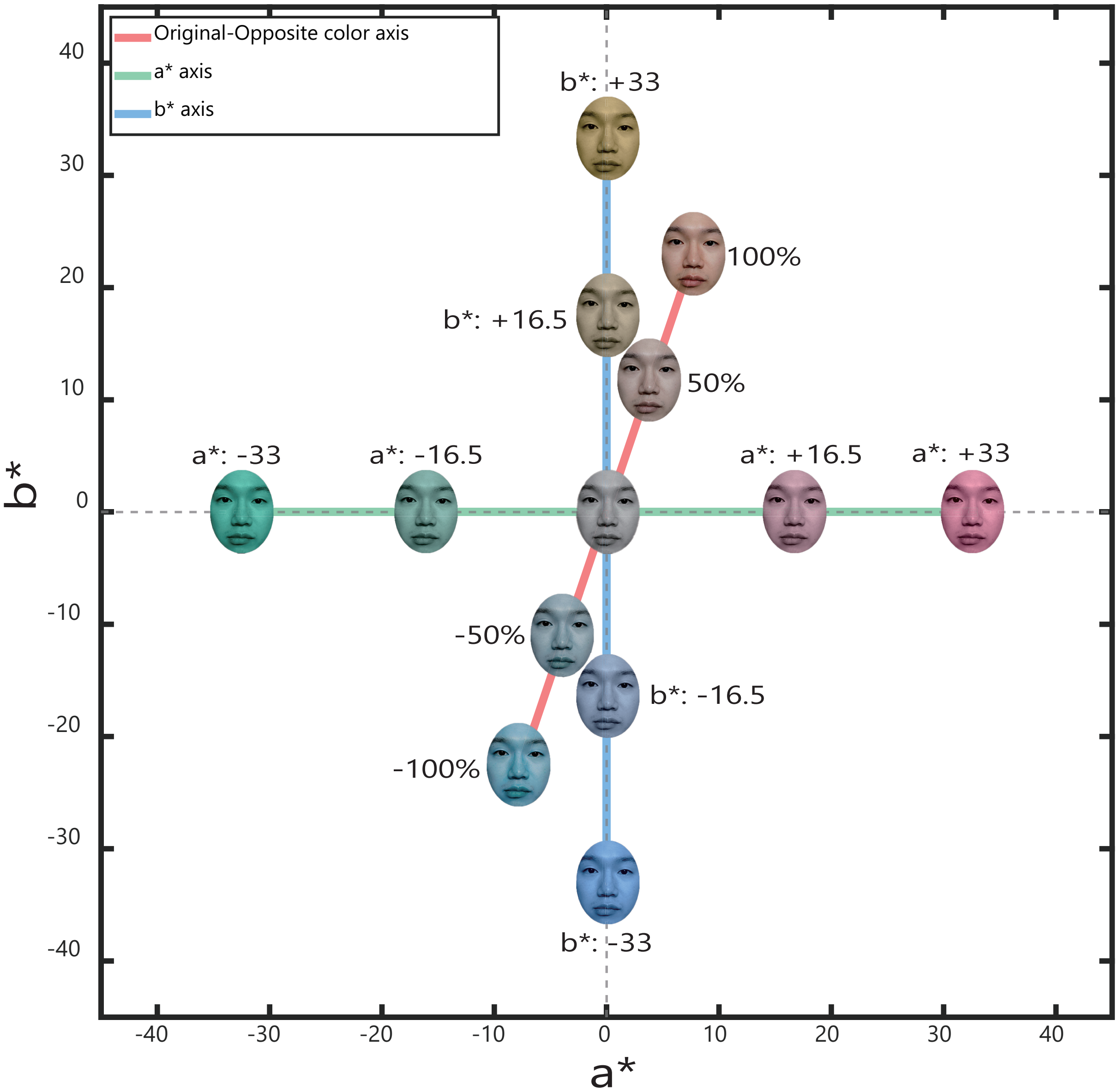

Fig. 3.3.1: Experimental stimuli (Exp.2)

Each axis of condition in Experiment 2. The original-opposite color axis in the figure is the average line of all the faces.

Procedure

Figure 3.3.2 illustrates the procedure used in Experiment 2. After a 0.5 s inter-stimulus interval and 1.0 s fixation were presented, the participants viewed a facial stimulus for 0.5 s. Then, the presentation of noise for 1.0 s to reduce the aftereffect. According to the instructions, the participant rated the color appearance of the presented facial stimulus using a numeric keypad (e.g., "4" opposite, "6" typical, in the original-opposite condition). The participants were instructed to respond intuitively, prioritizing accuracy.

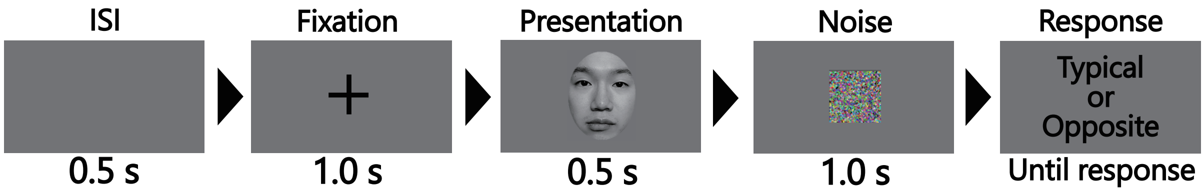

Fig. 3.3.2: Experimental procedure (Exp.2)

The choices were modified based on the conditions, such as "red" or "green" in condition a*, and "yellow" or "blue" in condition b*. There were 252 facial stimuli (4 individuals × 3 expressions [anger, neutral, fear] × 7 steps × 3 axis conditions), and each stimulus was assessed twice. Therefore, each participant completed 504 trials, which were divided into three blocks per axis condition with a counterbalanced block order among participants. Each block was subdivided into four sections, and participants could take breaks between sections and blocks.

Data analysis

Because of poor performance, I excluded participants whose selected facial color rates in conditions with minimum and maximum color changes were outside the plus and minus three sigma ranges of the participants' averages, respectively. Thus, two participants were excluded from the analysis, leaving 21 for further analysis. These participants might have found it difficult to judge color differences (which cannot be assessed in the color vision test chart) and may have deviated from the range I set based on the preliminary experiment.

In each condition, the facial color selection rates for each facial expression from each participant were fitted with a psychometric function using a generalized linear model with a binomial distribution in the MATLAB Palamedes Toolbox (Prins, 2013, 2023; Prins and Kingdom, 2018). The point of subjective equality (PSE) was computed, which is shown as the subjective achromatic point. I checked the normality of the data using the Shapiro-Wilk test. If the data were confirmed to be normal, I performed a repeated measure one-way analysis of variance using the statistical tool Anovakun version 4.8.5 in R. If the data did not follow a normal distribution, I performed a Friedman test. When a significant main effect on facial expression conditions was found by the Friedman test, I performed post hoc tests using the Wilcoxon test. The p values were adjusted using the Shaffer method in the post hoc tests.

3.3.2 Results

Original-opposite axis condition

Figure 3.3.3 shows the mean PSE for each facial expression. I found significant differences between facial expressions in the original-opposite condition ($\chi^2 = 14$, $p < 0.001$) as illustrated in Figure 3.3.3A. The post hoc test revealed that the subjective achromatic points of anger and fear were shifted more toward opposite colors than toward neutral faces: anger-neutral ($Z\left(20\right) = -2.07$, $adj.p < 0.05$, $r = 0.451$) and fear-neutral ($Z\left(20\right) = -3.53$, $adj.p < 0.001$, $r = 0.770$).

a* / b* axis condition

In contrast, there were no significant differences between facial expressions in the a* and b* conditions in Figures 3.3.3B and 3.3.3C, respectively (a* condition: $F\left(2, 40\right) = 0.60$, $p = 0.556$, ${\eta_p}^2 = 0.029$), (b* condition: $\chi^2 = 5.29$, $p = 0.071$).

3.3.3 Discussion

In original-opposite axis condition, the achromatic adjustment point of anger and fear faces shifted toward opposite color direction, compared with neutral faces. These findings suggest that participants perceived physically achromatic anger and fear faces as having a more typical color (skin tone) appearance compared to a neutral face. The memory colors of anger and fear faces exhibited a stronger skin tone component (higher saturation of red and yellow) compared to neutral faces. In contrast, the results in a* or b* axis conditions show that the achromatic adjustment points had no significant differences between facial expressions. These results suggested that angry faces do not necessarily appear reddish compared to other facial expressions and suggest that the memory color of the face depends on facial expression.

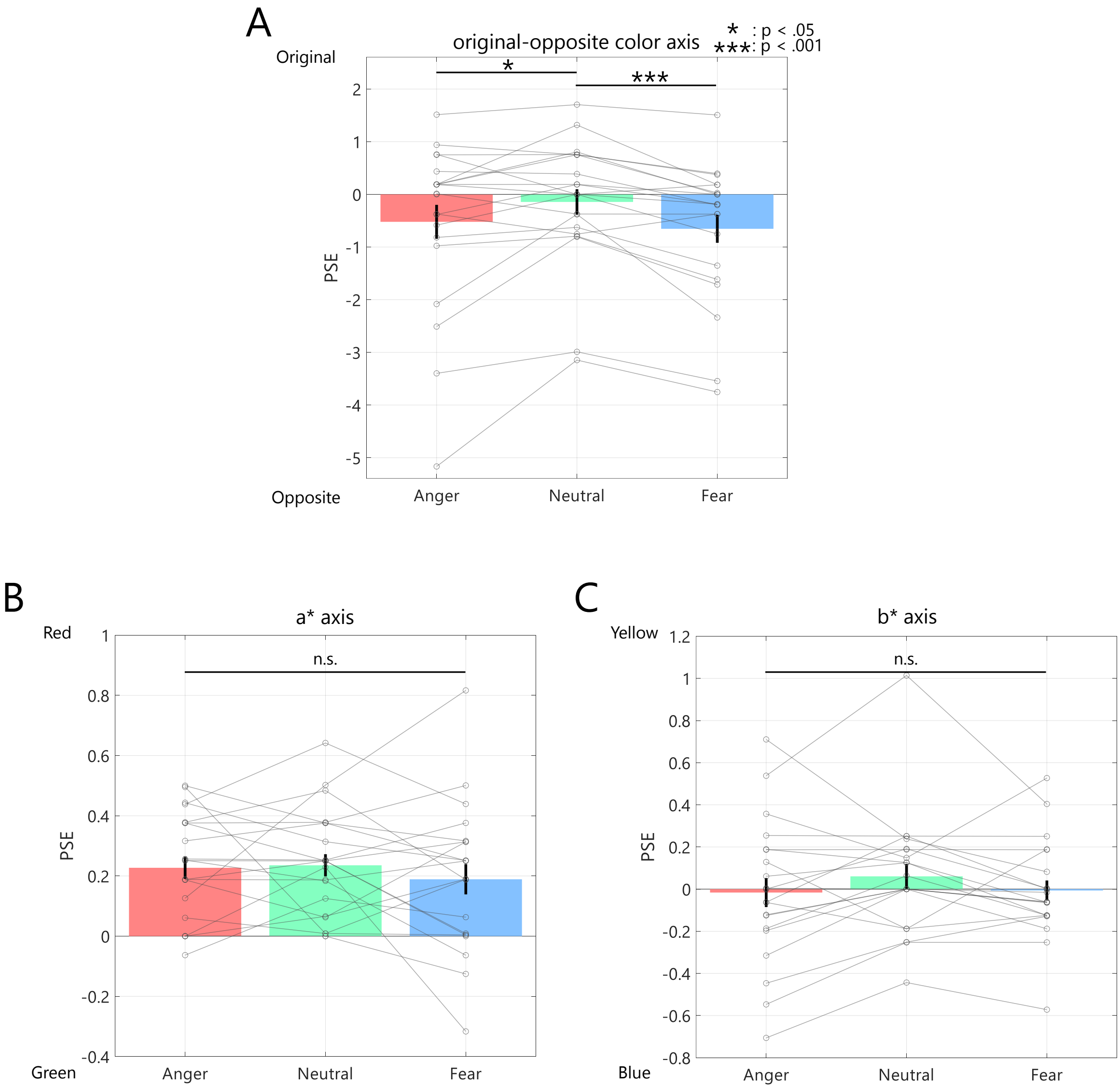

Fig. 3.3.3: Results (Exp.2)

Results of Experiment 2. Participants mean of PSE ([**A**] original-opposite color axis, [**B**] a* axis, [**C**] b* axis). The closer the value is to "0," the closer the subjective achromatic point is to the physical achromatic point. A larger positive value indicates that the subjective achromatic point is more shifted toward the original color (**A**)/red (**B**)/yellow (**C**), whereas a larger negative value indicates that the subjective achromatic point is more shifted toward the opposite color (**A**)/green (**B**)/blue (**C**). The other formats were the same as in Figure 3.2.3.

3.4 General discussion of this chapter

In this study, I estimated the effect of memory color on different facial expressions. To investigate this research question, I conducted the color adjustment task (Experiment 1) and the yes/no task (Experiment 2), comparing participants' subjective achromatic points of angry, neutral, and fearful faces. The results of Experiment 1 showed no significant differences between facial expressions in the color-adjusting task (Figure 3.2.3A). The results of Experiment 2 showed that the subjective achromatic points of anger and fear shifted more towards the opposite color than in the neutral condition (Figure 3.3.3A). This result is similar to that of previous studies on the memory color effect, wherein objects in a physically achromatic state appear to be colored in their memory color, and the subjective achromatic point shifts to the opposite (Hansen et al., 2006; Olkkonen et al., 2008). Therefore, the angry and fearful faces were shown to be more likely to cause color misperception than neutral faces because of the memory color effect, and it is suggested that the memory color of angry and fearful faces has stronger facial color components, such as reddish-yellowish (high saturation), than neutral. In addition, my result is also similar to the results of a previous study, which demonstrated stronger memorization/recall of the red-yellow (a* and b*) components than of the actual facial color, supporting the idea that the perception of emotional expressions can bias facial color memory (Thorstenson et al., 2021). The subjective achromatic point shifted to the opposite color in anger, supporting my hypothesis and aligning with the results of previous studies indicating that angry faces with a red-yellow component are more strongly memorized (Thorstenson et al., 2021). Although fear is typically associated with decreased redness and yellowness (Thorstenson et al., 2018), the subjective achromatic point of a fearful face was also shifted towards the opposite color, similar to anger. Another previous study reported that the perceived intensity of fear was enhanced not only in the green direction (a −) but also in the red direction (a; Thorstenson et al., 2022). Thus, it is possible to conclude that fearful faces evoke warm color effects, as well as cold color effects, and these warm color effects may manifest as memory color effects.

In the a* axis condition of Experiment 2 (Figure 3.3.3B), all subjective achromatic points tended to shift more toward the red (a*) direction than toward the physical achromatic point (one-sample t-test, anger: $t\left(20\right) = 5.78, p < 0.02$, Cohen's $d = 0.29$; neutral: $t\left(20\right) = 5.97, p < 0.001$, Cohen's $d = 0.30$; fear: $t\left(20\right) = 3.51, p < 0.05$, Cohen's $d = 0.25$). One possible reason for this is that the achromatic face may have been perceived as having a morbid complexion because the facial color of the stimuli was not realistic and had little red or yellow color (Hasantash et al., 2019; Stephen et al., 2009). Facial color plays an important role not only in emotions but also in attractiveness and health status (Thorstenson et al., 2019; Thorstenson and Pazda, 2021). Specifically, a pale face is difficult to consider healthy, and face color, in the presence of impaired retinal mechanisms for color, such as the scenes under low-pressure sodium light, appears to have a morbid greenish complexion (Hasantash et al., 2019; Stephen et al., 2009; Thorstenson et al., 2019). Thus, participants were more likely to perceive the face color in the physically achromatic state as greenish when judging reddish or greenish.

Facial expressions in the color adjustment experiment (Experiment 1) did not differ but did significantly differ in the color selection experiment (Experiment 2). One possible reason for this discrepancy is the differences in the presentation time and perception of color change between the two experiments. In Experiment 1, the participants had to constantly observe the stimuli to adjust their color to achromatic conditions and visualize the color change. Humans evaluate color differences in facial stimuli to a greater extent than in non-facial stimuli, suggesting that humans are more sensitive to changes in facial colors (Thorstenson et al., 2017). Additionally, Experiment 1 provided a paradigm in which near-achromatic colors with the same average luminance as the background color were always observed, which may have caused chromatic adaptation even though we did not test for it. Thus, future studies should note continuous color changes and prolonged presentations when testing the effects of memory color on faces.

4 EEG modulation by facial expression and color

Chapter 3 suggested that the memory color of faces varies depending on facial expression, especially, humans might memorize angry and fearful faces as having higher saturation than neutral faces. In this chapter, I investigated how the semantic congruency between facial expression and color affects EEG activity associated with top-down processing. This study explored whether the ERP reflecting selective attention are modulated by the interaction between facial expression and color.

An original version of this chapter has been published as:

Yuya Hasegawa, Hideki Tamura, Shigeki Nakauchi, & Tetsuto Minami. "Interaction between facial expression and color in modulating ERP P3." *eNeuro*, 12(1), 2025.

4.1 Introduction

The relationship between facial expression and facial color, especially the relationship between anger and red, affects cognitive function, such as human judgment and memory (Nakajima et al., 2017; Minami et al., 2018; Peromaa and Olkkonen, 2019; Thorstenson et al., 2021; Kato et al., 2022). Red angry faces increase the perception of anger (Nakajima et al., 2017), whereas angry faces increase selective attention (Öhman et al., 2001; Honk et al., 2001; Fox et al., 2002; Mogg et al., 2004). In the relationship between facial expression and selective attention, angry and fearful faces are known to bias visual attention, and it is believed that perceived threats may be among the factors that capture human attention (Öhman et al., 2001; Fox et al., 2002; Mathews et al., 2003). However, it is still unclear whether the relationship between facial expression and color affects selective attention and its brain activity, which are also modulated by facial expression. Therefore, I hypothesized that if selective attention to red angry faces is enhanced via top-down feedback from experiential memory, the brain activity associated with this process (e.g., ERP P3) would also be increased.

In this study, I aimed to clarify the effect of the relationship between facial expression and facial color on the P3, which reflects selective attention. The P3 amplitude varies in magnitude depending on the intensity of selective attention to the target. Therefore, I hypothesized that when the relationship between anger and red causes strong selective attention, an interaction effect of facial expression and facial color is exerted on P3 rather than a color effect alone. For example, the P3 amplitude for red angry faces is larger than that for red neutral faces, and this trend is more pronounced than when angry faces with normal facial color are compared with neutral faces with normal facial color. In this study, I recorded participants' EEG during an oddball task to investigate the effects of facial expression and facial color on EEG, which reflects selective attention. Then, I compared the P3 amplitudes to estimate how differences in facial expression and facial color influence selective attention. Additionally, I also examined the amplitudes of P1 and N170 to investigated whether the relationship between facial expression and color is observed from ERP stages prior to the P3.

4.2 Experiment

4.2.1 Materials and methods

Participants

Twenty Japanese students (five women and fifteen men; mean age, 22.50 ± 1.00 years) at Toyohashi University of Technology participated in the experiment. The sample size was calculated using PANGEA (Westfall et al., 2014) with an effect size of $d = 0.4$, $power = 0.8$, and $\alpha = 0.05$, and I found that 19 participants were needed. Assuming a possibility of data rejection due to any EEG artifacts, I recruited 20 participants. Before joining the experiment, the participants were provided with an introduction to the experiment, excluding the study's hypothesis, and gave informed consent. All participants had normal color vision, as verified by the Ishihara Color Vision Test Chart II Concise Version 14 Table (the Public Interest Incorporated Foundation Isshinkai, Handaya). This experiment was conducted with the approval of the Ethics Review Committee for Research Involving Human Subjects at Toyohashi University of Technology and adhered strictly to the approved guidelines of the committee and the Declaration of Helsinki. This study was not preregistered.

Stimuli and apparatus

The facial stimuli (Figure 4.2.1) were angry and neutral faces of two Japanese individuals (one woman and one man) obtained from the ATR Facial Expression Image Database (ATR-Promotions; https://www.atr-p.com/products/face-db.html). The hair, ears, and necks in the images were removed via Photoshop (Adobe Systems), with the edited image presenting an oval shape. All the images were adjusted to maintain an average image luminance of $16.9\,\mathrm{cd/m^2}$ via SHINE_color, a MATLAB 2021a toolbox (Willenbockel et al., 2010; Ben, 2021). Based on an experiment by Nakajima et al. (2017), I created colored facial stimuli by manipulating the a* (red-green) value in CIE L*a*b* (Nakajima et al., 2017). There were three facial color conditions: original (no manipulation), red (a*12 units), and green (a*-12 units). Twelve image stimuli (2 individuals $\times$ 2 facial expressions $\times$ 3 facial colors) were prepared. The image dimensions were $4.2\,\mathrm{deg} \times 5.5\,\mathrm{deg}$. The mean and standard deviation of the CIE L*a*b* values for the original faces were L* = 47.60 ± 0.06, a* = 7.61 ± 0.09, and b* = 22.41 ± 0.06. The background color was always gray ($Y = 17.09\,\mathrm{cd/m^2}$).

The experiment was conducted in a dark magnetically shielded room. The stimuli were presented on a monitor (VIEPixx/ EEG, VPixx Technologies; resolution: 1,920 $\times$ 1,080; frame rate $120\,\mathrm{Hz}$). The white point of the monitor was $[x, y] = [0.30, 0.33]$, $Y = 91.23\,\mathrm{cd/m^2}$. The participants were seated and performed the task while keeping their heads on a chin rest positioned 60 cm from the display. Psychtoolbox 3.0.17 served as the experimental control software (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007). EEG data were acquired via 64 channels of electrodes and six channels of external sensors at a sampling frequency of $512\,\mathrm{Hz}$ via BioSemi ActiveTwo and recorded via the ActiveTwo System.

Procedure

In the experiment, I used six image stimulus pairs. Three pairs were prepared for each face stimulus (two persons): the original color angry face and original color neutral face, the red angry face and red neutral face, and the green angry face and green neutral face. An oddball task was performed with the high-frequency stimulus as the standard stimulus and the low-frequency stimulus as the target stimulus in these pairs. In each trial, when the target stimulus was a red angry face, the standard stimulus was a red neutral face, and when the target stimulus was a red neutral face, the standard stimulus was a red angry face. Therefore, a participant performed 12 trials (6 pairs $\times$ 2 targets) of the oddball task in total. Standard and target stimuli were presented in a random order during each trial. The frequency of standard and target stimuli was always Standard:Target = $1 : 4$, and the target stimulus was presented

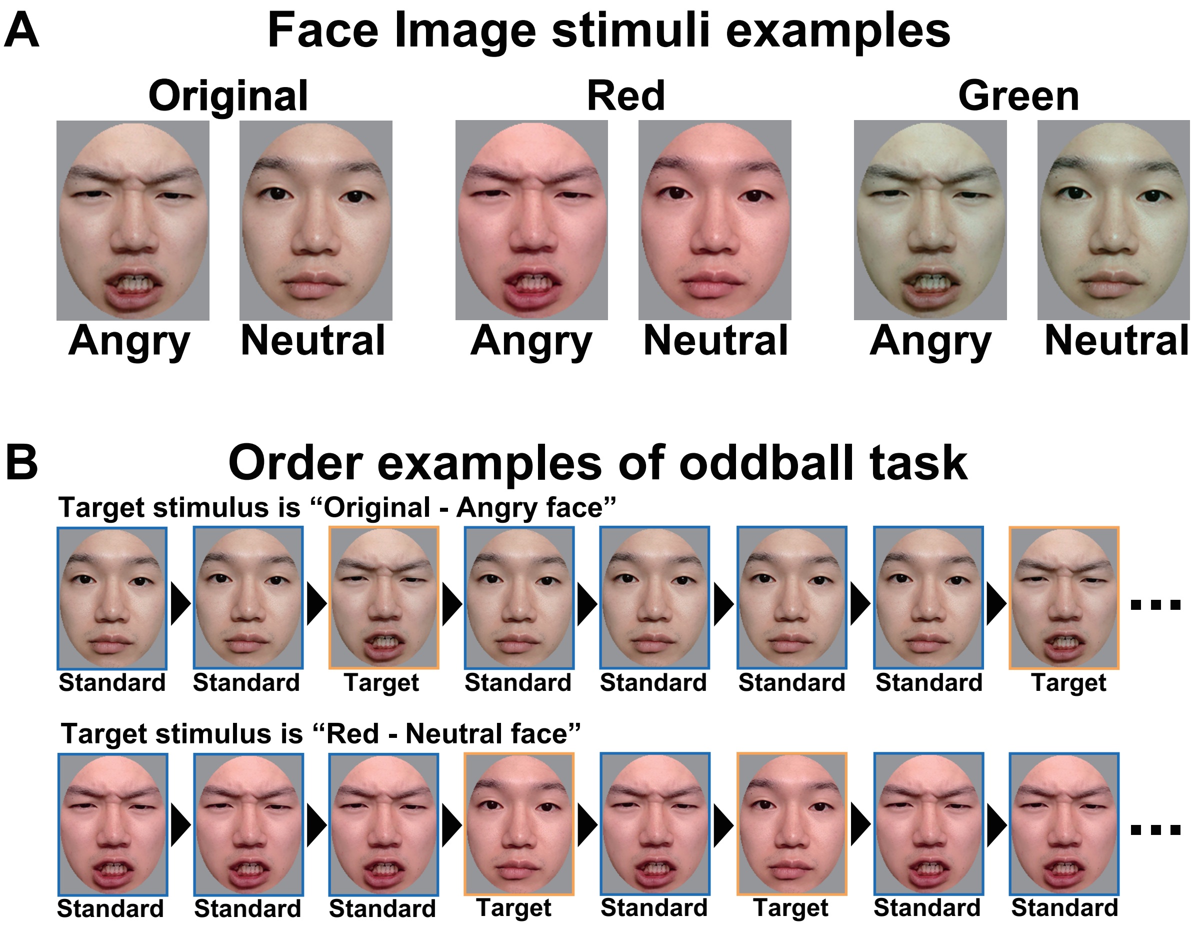

Fig. 4.2.1: Experimental stimuli

(A) Examples of the image stimuli for each condition. There were two facial expression conditions, angry and neutral, and three facial color conditions, original (no manipulation), red (a* 12 units), and green (a* −12 units). Two face models (1 woman and 1 man) were used for each of the six conditions (2 facial expression × 2 facial color). **(B)**, Examples of presentation order for the oddball task. Standard stimuli are presented at high frequency, and target stimuli are presented at low frequency. The faces in the figure are from one of the authors (Y.H.) and were not used in the experiment.

10–15 times. The participants were asked to count the number of times the target stimulus appeared. Figure 4.2.2 shows a summary of the experimental procedure. First, a task description was presented until the participant pressed the enter key. After a 1.0 s interstimulus interval, the fixation points and facial expression stimuli (standard or target stimulus) were presented repeatedly at 0.5 s intervals. After the end of the presentation, the participant recorded the number of times the specified facial stimulus (target stimulus) appeared via a numeric keypad. The experiment was conducted in two blocks, one for counting angry faces and one for counting neutral faces (6 trials per block), and the order of the blocks differed among the participants. The order of the six pairs (2 persons $\times$ 3 facial color) presented within a block was random. The participants could take breaks between trials and blocks. The participants wore EEG equipment throughout the experiment, and their EEGs were recorded during the task. Additionally, to reduce motion noise, the participants were instructed to avoid counting with their fingers or voices.

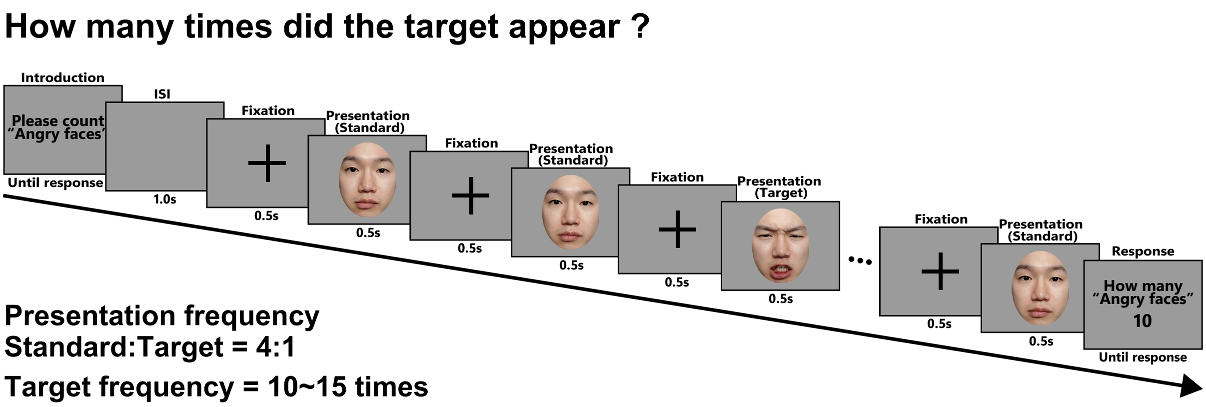

Fig. 4.2.2: Experimental procedure

Procedure of the experiment when the target stimuli are angry faces. In the repetition presentation phase, the stimuli were presented in a random order with a frequency of Target:Standard = 1:4. After the presentation phase, the participant recorded the number of times the specified facial stimulus (target stimulus) appeared in the instruction phase using a numeric keypad. The ratio among the number of text screens, fixation crosses, and stimuli depicted in this figure differs from the actual ratio.

Data analysis

Preprocessing of EEG data

For preprocessing, the EEG data were downsampled to 200 Hz, and a high-pass filter (1 Hz) and the function "cleanLineNoise" in EEGLAB were applied to eliminate line noise such as white noise, power supply noise (60 Hz), and its harmonic frequencies (120, 180, and 240 Hz). The significance cutoff level was $p = 0.01$. Additionally, electrodes that did not measure the data well were removed via the function "clean_rawdata" in the EEGLAB tool (unchanged interval: 5 s, correlation with surrounding electrodes: < 0.85, far from average: 4 times the standard deviation, removal via the ASR algorithm). The electrode data excluded by "clean_rawdata" were subsequently interpolated via the spherical spline interpolation method via the use of peripheral electrode data. Moreover, artifact removal was performed by eliminating ocular components via adaptive mixture independent component analysis (AMICA) and ICLabel (Leutheuser et al., 2013; Pion-Tonachini et al., 2019). Finally, I set the time of stimulus presentation as 0 ms and extracted the EEG data at −100 to 1,000 ms. One participant was excluded from the analysis because this preprocessing excluded all EEG data of target stimuli for one condition.

Statistical analysis

ERP P3

First, I extracted the channel-averaged EEG at Cz, CPz, CP1, CP2, and Pz from the preprocessed EEG. The baseline EEG was the average EEG of −100 to 0 ms. Next, the mean amplitudes at 300–500 ms after the presentation of the standard and target stimuli were calculated for each trial. In this experiment, the time windows and channels used were predefined during the experimental design phase based on previous research (Polich, 2007; Hinojosa et al., 2015; Che et al., 2024). Then, the mean amplitude of the standard stimulus was subtracted from the mean amplitude of the target stimulus during the same trial, and I calculated the average for each of the facial expression (anger, neutral) and facial color (original, red, green) conditions (for a total of six conditions). Quartile range exclusion was subsequently performed for each condition to exclude outliers. Thus, the data of one participant with an outlier outside the interquartile range were excluded. Therefore, the final statistical analysis included 18 participants.

I first conducted the Shapiro-Wilk test to confirm that the data were normally distributed. If the data were normal, I performed a repeated-measures two-way analysis of variance using R; otherwise, I performed a nonparametric test with nparLD, an R software package (Noguchi et al., 2012). ANOVA-type statistics (ATS) were calculated via nonparametric tests. Moreover, the p values were subjected to post hoc correction via the Holm method.

ERP N170

I extracted the channel-averaged EEG at five channels near the temporal area (left: TP7, P5, P7, P9, PO7; right: TP8, P6 P8, P10, PO8) from the preprocessed EEG. The baseline time window was the same as that for the P3 amplitude. Then, the peak amplitudes at 150–200 ms after the presentation of the target stimuli were calculated for each trial, and I averaged them for each condition via the same method as that used for the P3. Afterward, the same statistical analysis as that used for P3 was performed on the left and right peak amplitudes. I used the same participant data as those used in the statistical analysis of the P3.

ERP P1

I extracted the channel-averaged EEG at Iz, Oz, O1, O2, and POz from the preprocessed EEG. The baseline time window was the same as that for the P3 and N170 amplitudes. The P1 amplitude was calculated via the same procedure used for N170, except that the time window of the peak amplitude was $80–120\,\mathrm{ms}$. Afterward, the same statistical analysis as that used for P3 was performed on the left and right peak amplitudes.I used the same participant data as those used in the statistical analysis of the P3.

4.2.2 Results

ERP P3

Figure 4.2.3 shows the average wave for the target and standard stimuli for each condition. Figure 4.2.4 shows the mean P3 amplitude for each facial expression and facial color condition. I found a significant main effect of facial expression ($F\left(1, 17\right) = 10.089$, $p < 0.01$, ${\eta_p}^2 = 0.372$) and a significant interaction effect between facial expression and facial color ($F\left(1.97, 33.48\right) = 3.747$, $p < 0.05$, ${\eta_p}^2 = 0.181$). The post hoc results revealed that the P3 amplitude for angry faces was greater than that for neutral faces ($t\left(17\right) = 3.176$, $p < 0.01$, Cohen's $d = 0.749$), and the P3 amplitude for red angry faces was greater than that for red neutral faces ($t\left(17\right) = 3.382$, $p < 0.01$, Cohen's $d = 0.797$). The other statistical analysis results for P3 are shown in Tables 4.2.1–4.2.4.

Table 4.2.1: Summary of two-way repeated-measures ANOVA results for P3

Effect	F	df^{GG}	$df^{\mathrm{GG}}_{\mathrm{res}}$	p	${\eta_p}^2$
Expression	10.09	1	17	0.006	0.372
Color	0.22	1.80	30.53	0.784	0.013
Expression × color	3.75	1.97	33.48	0.035	0.181

Table 4.2.2: Post hoc comparisons of expression (P3)

Contrast	t	95 %CI	df	p	Cohen's d
Angry-neutral	3.18	[0.20, 1.01]	17	0.006	0.75

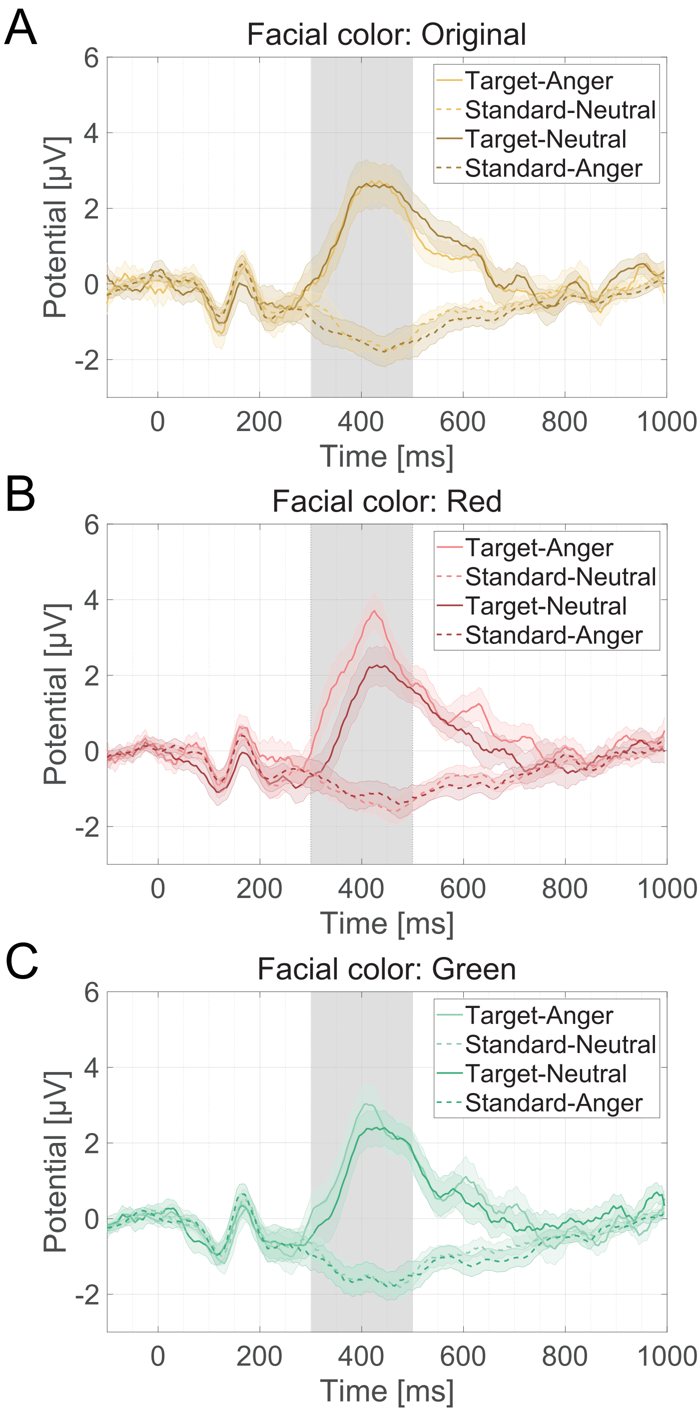

Fig. 4.2.3: EEG wave plots

Channel-averaged EEG waves of the mean for each condition (**A**, original; **B**, red; **C**, green). The bands covering the unbroken curve and the dashed curve represent the standard error of the mean. The gray bands at 300–500 ms are the time windows of P3 analysis. The data were smoothed for plotting and were not used in the analysis.

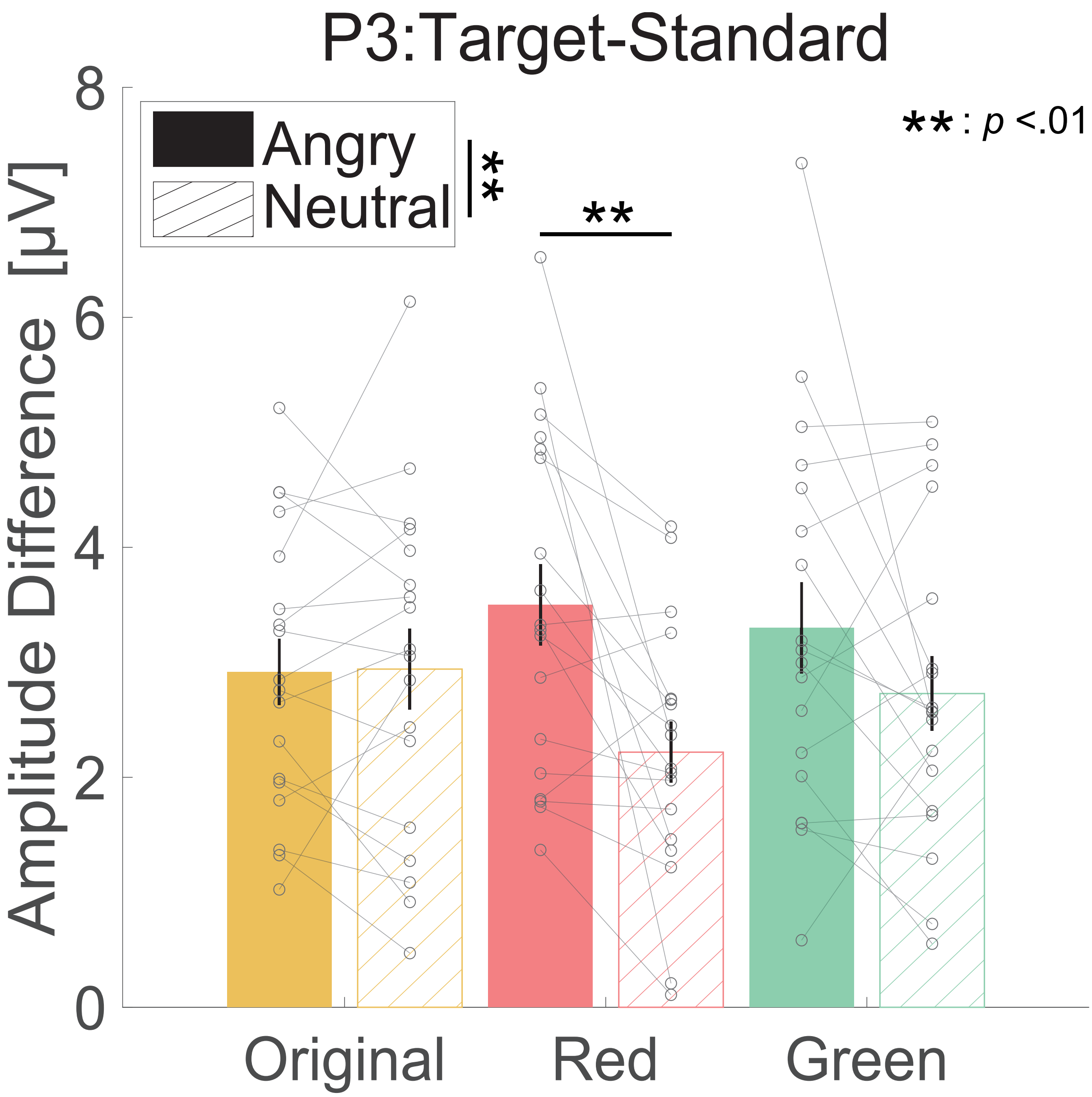

Fig. 4.2.4: Results of P3

Mean of the difference in P3 amplitude [µV] for target and standard stimuli. Each gray point represents individual data. The color of each bar and the label on the horizontal axis indicate facial conditions. The filled and hatched bars indicate that target stimuli were angry faces and neutral faces, respectively. Error bars show the standard error of the mean.

Table 4.2.3: Summary of main effects analysis for expression × color interaction (P3)

Effect	F	df^{GG}	$df^{\mathrm{GG}}_{\mathrm{res}}$	p	${\eta_p}^2$
Expression at original	0.01	1	17	0.914	0.001
Expression at red	11.44	1	17	0.004	0.402
Expression at green	2.28	1	17	0.150	0.118
Color at angry	1.44	1.97	33.42	0.252	0.078
Color at neutral	2.70	1.70	28.98	0.092	0.137

Table 4.2.4: Post hoc comparisons of expression at red (P3)

Contrast	t	95 %CI	df	p	Cohen's d
Angry-neutral	3.38	[0.48, 2.08]	17	0.004	0.80

ERP N170

Figure 4.2.5 shows the mean N170 amplitude for each facial expression and facial color condition. I found a significant main effect of facial expression on the left and right sides (left: $ATS\left(1\right) = 6.940$, $p < 0.01$; right: $F\left(1, 17\right) = 10.100$, $p < 0.01$, ${\eta_p}^2 = 0.373$). Post hoc tests revealed that the N170 amplitudes for angry faces were greater than those for neutral faces (left: $Z\left(17\right) = -2.896$, $p < 0.01$, $r = 0.683$; right: $t\left(17\right) = -3.178$, $p < 0.01$, Cohen's $d = 0.749$). These results are similar to those of previous studies, which revealed larger N170 amplitudes for negative facial expressions than for neutral facial expressions. The other statistical analysis results for N170 are shown in Table 4.2.5–4.2.8

Table 4.2.5: Summary of nonparametric ANOVA results for N170 left

Effect	F	df	p
Expression	6.94	17	0.008
Color	0.47	1.96	0.621
Expression × color	0.63	1.94	0.529

Table 4.2.6: Post hoc comparisons of expression (N170 left)

Contrast	Z	df	p	r
Angry-neutral	-2.90	17	0.002	0.68

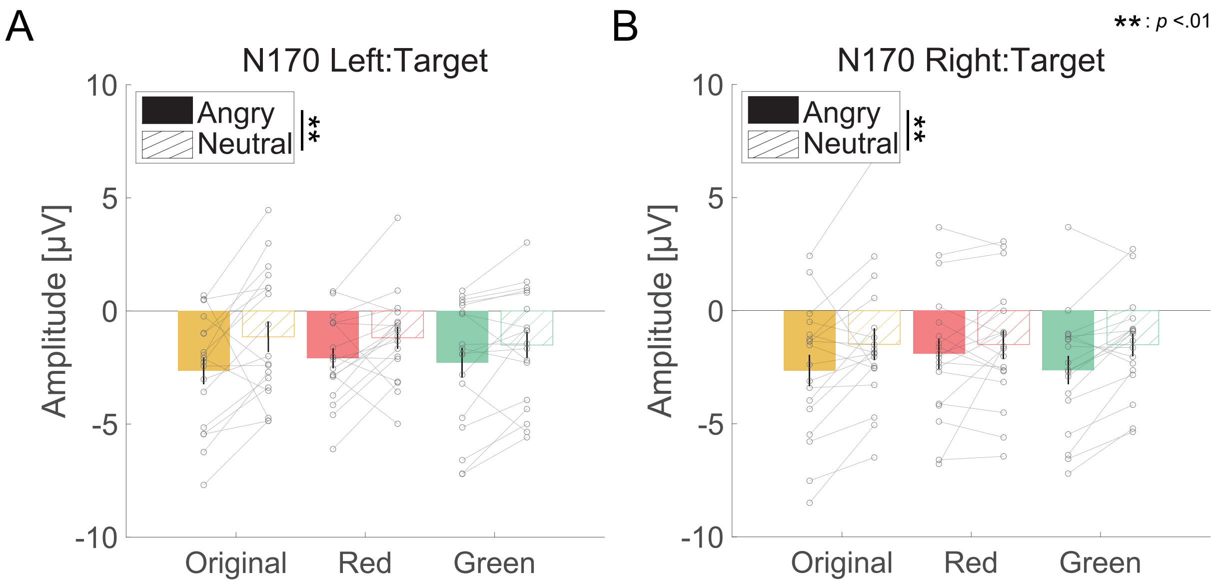

Fig. 4.2.5: Results of N170

Mean of the N170 amplitude [μV] for target stimuli (**A**, left side; **B**, right side). The color of each bar and the label on the horizontal axis indicate facial conditions. The filled and hatched bars indicate that target stimuli were angry faces and neutral faces, respectively. Error bars show the standard error of the mean.

Table 4.2.7: Summary of two-way repeated-measures ANOVA results for N170 right

Effect	F	df^{GG}	$df^{\mathrm{GG}}_{\mathrm{res}}$	p	$\eta_p{}^2$
Expression	10.10	1	17	0.006	0.373
Color	0.64	1.68	28.54	0.508	0.036
Expression × color	1.31	1.97	32.18	0.283	0.071

Table 4.2.8: Post hoc comparisons of expression (N170 right)

Contrast	t	95 %CI	df	p	Cohen's d
Angry-neutral	-3.18	[-1.49, -0.30]	17	0.006	0.75

ERP P1

Figure 4.2.6 shows the mean P1 amplitude for each facial expression and facial color condition. No significant main effect or interaction effect of facial expression and facial color was exerted (Table 4.2.9).

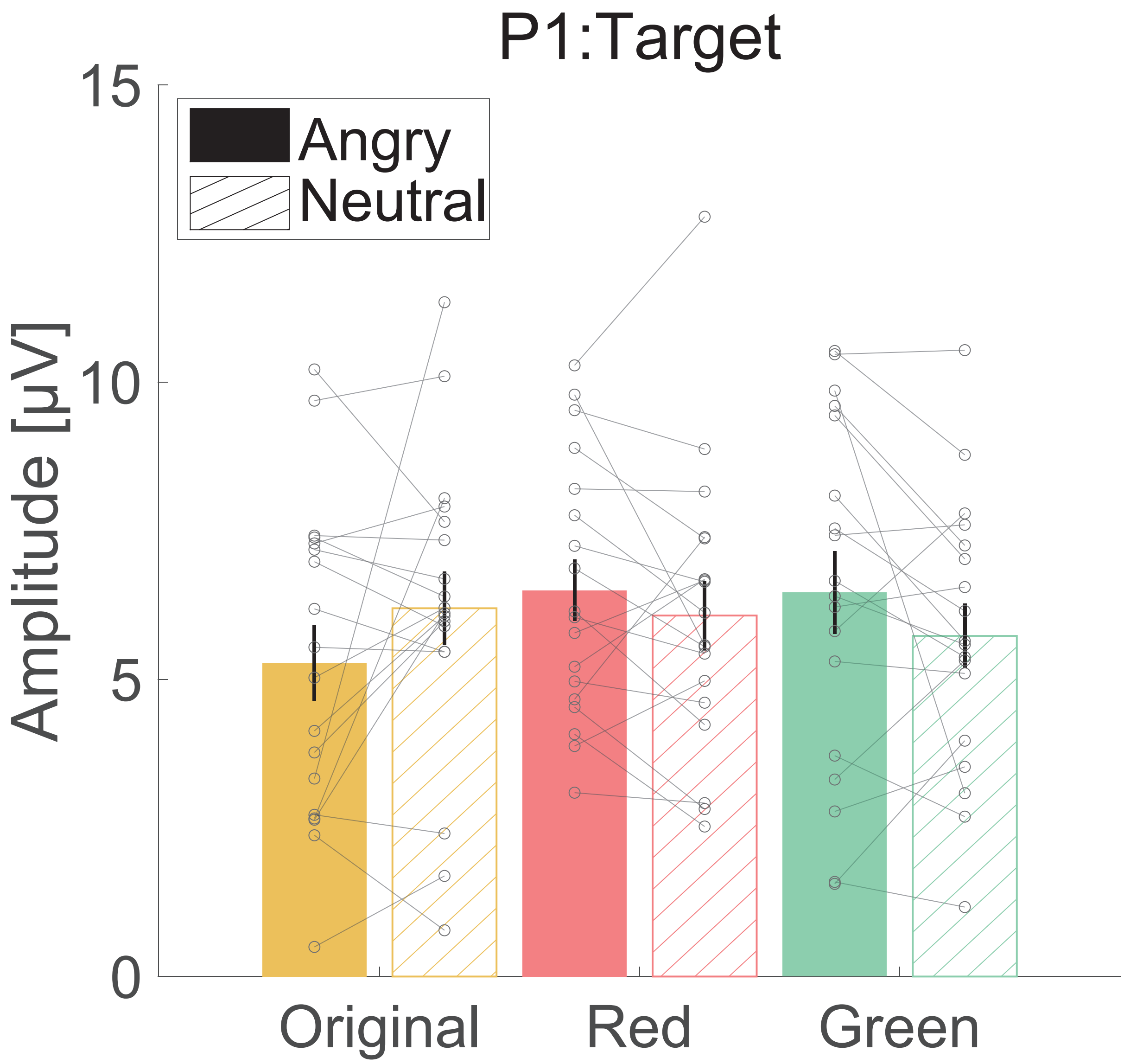

Fig. 4.2.6: Results of P1

Mean P1 amplitude [µV] for target stimuli. The color of each bar and the label on the horizontal axis indicate facial conditions. The filled and hatched bars indicate that target stimuli were angry faces and neutral faces, respectively. Error bars show the standard error of the mean.

Table 4.2.9: Summary of two-way repeated-measures ANOVA results for P1

Effect	F	df^{GG}	$df^{\mathrm{GG}}_{\mathrm{res}}$	p	${\eta_p}^2$
Expression	0.06	1	17	0.802	0.004
Color	1.05	1.85	31.53	0.357	0.058
Expression × color	3.11	1.52	25.90	0.074	0.155

4.3 Discussion

In this study, I used an oddball task to investigate whether the relationship between facial expression and facial color influences selective attention and recorded participants' EEGs during the task. The results revealed that the P3 amplitude for red angry faces was greater than that for red neutral faces, suggesting that the EEG activity associated with the selective attention given to angry red faces was greater than that given to neutral red faces. In addition, previous research has reported that the P3 amplitude is modulated due to semantic relevance (Kok, 2001). Since the task in this experiment involved counting the specified facial expressions, the increase in P3 amplitude for the red angry face might be attributed to the semantic congruence between the emotion and the color as a contributing factor. Furthermore, P3 and selective attention are thought to be enhanced in response to threats (Öhman et al., 2001; Kessels et al., 2014). It has been reported that intensifying the redness of angry faces increases perceived emotional intensity, aggression, and threat (Thorstenson and Pazda, 2021; Thorstenson et al., 2022). Therefore, the increase in P3 amplitude for red angry faces might also be attributed to the observer's strong sense of threat for that face stimulus.

Moreover, facial expression and facial color had no main effect or interaction effect on the P1 amplitude, and facial expression had only a main effect on the N170 amplitude. In contrast, a main effect of facial expression and an interaction effect between facial expression and facial color were exerted for the P3 amplitude. These results indicate that the relationship between facial expression and facial color is represented by higher-order processing along the P1, N170, and P3 time axes. P1 amplitudes reflect the initial attentional processing of stimuli, and N170 amplitudes reflect differences in facial expression (Hillyard and Anllo-Vento, 1998; Hinojosa et al., 2015). In contrast, P3 amplitudes reflect higher-order cognitive processing, such as conscious attention (Polich, 2007). Hence, these findings suggest that enhancing responses resulting from the interaction between facial expressions and color are observed at later ERP stages than at early ERP stages associated with facial and facial color processing. As mentioned above, the P3 amplitude is modulated in association with stimuli (Kok, 2001). Additionally, involuntary differentiation processing for expressions is reported to occur later than N170 (Eimer and Holmes, 2002; Wronka and Walentowska, 2011). Therefore, the increased P3 amplitude for red angry faces might have been caused by the semantic processing of anger and red and later processing stages, such as the differentiation of facial expressions rather than simple facial color or expression processing.

In addition, the P3 amplitude, which reflects selective attention, is associated with memory. P3 is also an indicator of the degree of encoding and recall, and previous studies have suggested that a high P3 amplitude indicates the importance of encoding and the degree of successful recall (Karis et al., 1984; Fabiani et al., 1986; Polich, 2007). Emotionally relevant stimuli are known to be more strongly anchored in memory than are neutral stimuli, and the results of this study suggest that red angry faces have a greater influence on human memory (Dolcos and Cabeza, 2002). These results support previous studies that suggest that facial color memory for angry faces is biased toward more reddish and yellowish colors than that for actual facial color or neutral faces (Thorstenson and Pazda, 2021; Hasegawa et al., 2024).

It is known that the amygdala plays an important role in the enhancement of attention and perception for emotional stimuli (e.g., Phelps and LeDoux, 2005). In addition, it has been reported that the hippocampus predicts attention benefits from implicit context memory (Goldfarb et al., 2016). Moreover, Fenker et al. (2005) suggested that the amygdala and hippocampus contribute to the retrieval of emotionally contextualized memories by coordinating the reactivation of representations stored in neocortical regions, such as the fusiform face area (FFA; Fenker et al., 2005). Accordingly, I propose the following hypothesis to account for the observed modulation of the ERP P3 component by the interaction between anger and the color red, which reflects unintentional modulation of selective attention. Specifically, the hippocampus might supply stored semantic knowledge, and the amygdala provides feedback related to emotion or threat relevance. Through their coordinated engagement driven by the semantic congruency between anger and red, these processes might enhance top-down processing such as selective attention, thereby modulating perceptual processing. Future studies will focus on these brain regions and their activity patterns to further elucidate the neural mechanisms underlying the modulation.

The results of this study revealed that the N170 amplitude depended on facial expression, with the N170 amplitudes for angry faces being larger than those for neutral faces. These results support findings from previous studies that emotional relatedness increases the N170 amplitude during facial processing (Hinojosa et al., 2015). However, the N170 amplitude did not differ among facial colors. The N170 amplitude reflects facial color processing, and the amplitude increases with respect to the unnaturalness of facial color (Minami et al., 2011; Nakajima et al., 2012). The stimuli used in this experiment had a color change of a*+12 units, which is considered not unnatural as a facial color. Thus, my results suggest that the a*+12 level of facial color change does not affect the N170 amplitude. This finding is also consistent with the results of Nakajima et al. (2012), where the N170 amplitude when the hue angle was changed in the red direction ($-45\,\mathrm{deg}$ when the original color was $0\,\mathrm{deg}$) did not differ from the N170 amplitude for the normal facial color (Nakajima et al., 2012).

The limitations of this study are as follows. The P3 amplitude is modulated not only by selective attention but also by factors such as memory performance and cognitive load (Polich, 2007; Minami et al., 2009). Consequently, the results of this study alone are insufficient to definitively establish whether the interaction between facial expression and color affects selective attention, and behavioral experiments showing increased selective attention to stimuli should be conducted.

5 The effect of facial color change on judgment

Chapter 3 and Chapter 4 suggested that the cognitive modulation arising from the semantic congruency between facial expression and color occur even under unintentional bias conditions. In this chapter, I extended previous research on modulation of responses, which has been examined using static facial color conditions, to dynamic changes in facial color. This study investigated how differences in facial color changes, including dynamic change and static conditions, influence the facial expression judgments.

An original version of this chapter has been published as:

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5.1 Introduction

Facial features such as the mouth, eyebrows, and eyes play important roles in facial emotion recognition (Beaudry et al., 2014; Benitez-Quiroz et al., 2018; Sadr et al., 2003; Wegrzyn et al., 2017). For example, angry faces are typically characterized by furrowed or lowered eyebrows, eyes that are wide open with tightened lower lids, and an elevated upper lip and a lowered lower lip, which exposes the teeth and stretches the corners of the mouth (Kohler et al., 2004). In addition to these static shape factors, dynamic facial changes also help in recognizing emotions. Human faces undergo dynamic changes, and dynamic changes in facial expressions facilitate the perception of emotion (Ambadar et al., 2005; Fujimura and Suzuki, 2010; Krumhuber et al., 2013; Recio et al., 2011; Trautmann et al., 2009). For example, compared with static facial expression stimuli, stimuli that involve dynamic changes in facial expressions are associated with greater accuracy in the judgment and categorization of emotions (Ambadar et al., 2005; Fujimura and Suzuki, 2010). In addition to facial expressions, a person's facial color changes depending on emotion (Drummond et al., 2001; Kreibig, 2010). For example, physiological responses such as heart rate, blood pressure, and skin temperature change in relation to emotional states (Kreibig, 2010). Additionally, facial blood flow increases when people express anger, leading to facial redness (Drummond et al., 2001). Thus, several relationships exist between emotions and facial colors.

Although facial changes are dynamic in nature, static facial color stimuli have been used in many previous experiments (e.g., Nakajima et al., 2017). Most studies that incorporate dynamic changes have examined changes in both facial expression and color together or have focused solely on dynamic changes in facial expression. Thorstenson et al. (2022) reported that facial stimuli with dynamic changes in expression and color generally facilitated a more accurate categorization of emotion than the absence of changes in facial color did. However, that study did not compare dynamic changes to facial color with precolored changes to facial color (i.e., facial colors that are consistently reddish and yellowish) but investigated only the effects of facial coloration. Therefore, the influence of dynamic changes in facial color alone on facial expression recognition remains unclear. For example, the judgment of facial expression depends on the color of the face, but it is uncertain whether this effect differs if the facial color is dynamic or static. Nakajima et al. (2017) reported that participants were more likely to perceive and judge reddish facial stimuli as angry than original facial color stimuli. Is this increased perception of anger further enhanced by dynamic changes in facial coloration?

This study aimed to clarify the effects of dynamic changes in facial color on the identification of facial expressions. I conducted a facial expression judgment task with the following hypothesis: If dynamic changes to facial color bias people's recognition of facial expressions more than static facial color does, then the perception of anger will be stronger when the facial color changes from neutral to red than when the facial color is consistently red. On the basis of a study by Nakajima et al. (2017), I performed experiments in which the participants selected the emotion of a morphed facial expression stimulus with either a dynamic or static facial color from two choices, and I compared the level of facial perception between the facial color conditions. In this study, to investigate only the effects of dynamic facial color changes on facial expression identification, I employed image stimuli in which the facial expressions were kept static (i.e., without any changes in facial shape in one presentation), and only the facial color dynamically changed.

5.2 Red vs. Original facial color (Experiment 1)

I conducted a facial expression judgment task to investigate the effects of differences in facial color and the presence or absence of changes in facial color on the recognition of facial expressions according to the methods outlined by Nakajima et al. (2017).

5.2.1 Materials and methods

Participants

Twenty-two Japanese students (9 females and 13 males; average age, 21.6 $\pm$ 1.05 years, between 18 and 24 years) at Toyohashi University of Technology participated in Experiment 1. The sample size was calculated using PANGEA with effect sizes of d = 0.5, α = 0.05, and $power \geq 0.8$ (Westfall et al., 2014). I used the Ishihara Color Vision Test Chart Ⅱ Concise Version 14 Table (Public Interest Incorporated Foundation Isshinkai, Handaya Co., Ltd., Tokyo, Japan) to check the participants' color vision. All of the participants had normal color vision, as verified by the test chart. They were introduced to the experiment (while being kept blinded to the hypothesis of the study), and they provided informed consent to participate. This experiment was conducted with the approval of the Ethics Review Committee for Research Involving Human Subjects at Toyohashi University of Technology.

Stimuli and apparatus

An 11-step morphing of facial images from fearful (0) to angry expressions (10), as in a previous study (one female, one male; Nakajima et al., 2017), was used in this experiment. The facial color of each image was changed across four conditions (see Figure 5.2.1). In the facial color change conditions, the color was changed from original (a*: ±0) to red (12) or from red to original in the CIEL*a*b* color space (mean CIELAB original; L* = 42.5 ± 0.04, a* = 5.8 ± 2.02, b* = 21.5 ± 1.34). However, notably, because the a* value was added to the original facial color, the color of the red condition was not categorically "red" but a relatively red or redder facial color. The facial color changed linearly over the course of 1 second, and each condition was defined as "OR (original to red)" or "RO." To compare the facial color change and no-change conditions, I provided the original (±0) and red (12) facial colors in the no-change conditions, under which the facial color did not change at all. I defined these conditions as "OO" (original to original = consistently original) and "RR." The changes in color value and duration of stimulus presentation were determined on the basis of previous research (Nakajima et al., 2017; Thorstenson et al., 2021). The size of the stimuli was $3.14\,\mathrm{deg} \times 3.14\,\mathrm{deg}$, and the background color was always gray (x = 0.30, y = 0.34, Y = 21.0 cd/m^2).

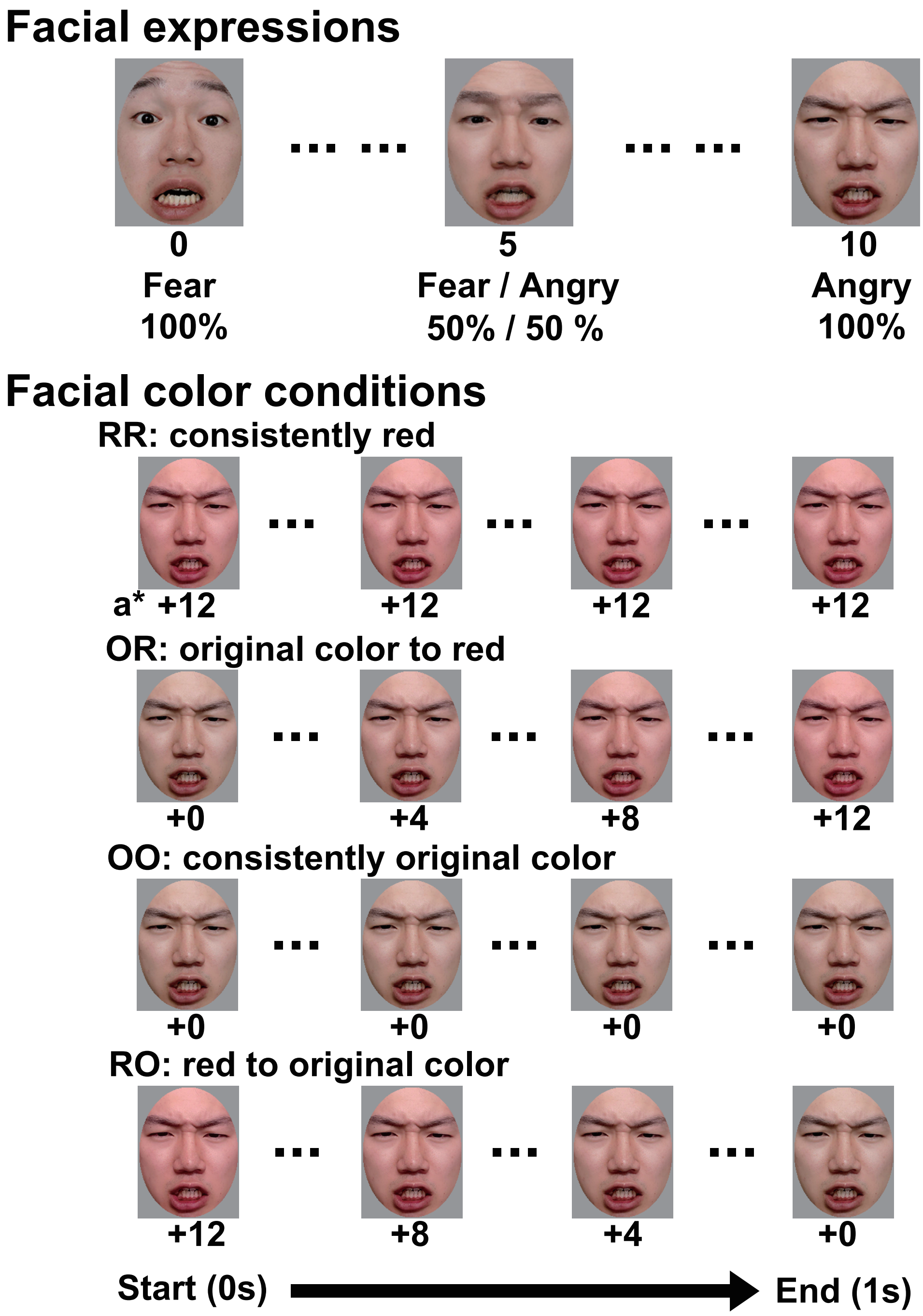

Fig. 5.2.1: Experimental stimuli (Exp.1)

Examples of the image stimuli for each condition in Experiment 1. An 11-step (0, most fearful, to 10, most angry) morphing of facial stimuli was used. See Nakajima et al. (2017) for more specific morphing image stimuli. Four facial color conditions were provided using red and the original color. The faces in the figure belong to one of the authors (YH) and were used with his permission but were not used in the experiment.

The experiments were conducted in a dark booth. The stimuli were presented on a monitor (EIZO CG319X with resolution of 1920 × 1080 and frame rate of 60 Hz; EIZO Corporation, Hakusan, Ishikawa, Japan) that was calibrated with SpyederX Elit (Datacolor, Lawrenceville, NJ) and ColorNavigator 7 (color management software provided by EIZO). The white point chromaticity of the monitor was $x = 0.30$, $y = 0.33$, $Y = 92.2\,\mathrm{cd/m^2}$. The participants were seated and performed the task while keeping their head on a chin rest positioned 85 cm from the display. MATLAB R2024a (MathWorks, Natick, MA) and Psychotoolbox 3.0.17, a toolbox of MATLAB, served as the experimental control software (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

Procedure

On the basis of previous studies (Nakajima et al., 2017), I conducted a facial expression judgment task. A summary of the experimental procedure is shown in Figure 5.2.2. After a 0.5 s interstimulus interval and 1.0 s fixation were presented, the participants viewed a facial stimulus for 1.0 s. Afterward, colorful noise was provided for 1.0 s to reduce the aftereffects of the facial expression judgment phase. The participants identified the facial expression of the presented stimulus as "anger" or "fear" via a numeric keypad. The participants were instructed to respond intuitively and to prioritize accuracy. There were 88 facial stimuli (11 step morphed faces × 2 individuals × 4 facial color conditions), and each stimulus was presented five times in random order (a total of 440 trials per participant). The experiment consisted of 44 trials in one block (a total of 10 blocks). The participants could take breaks between blocks.

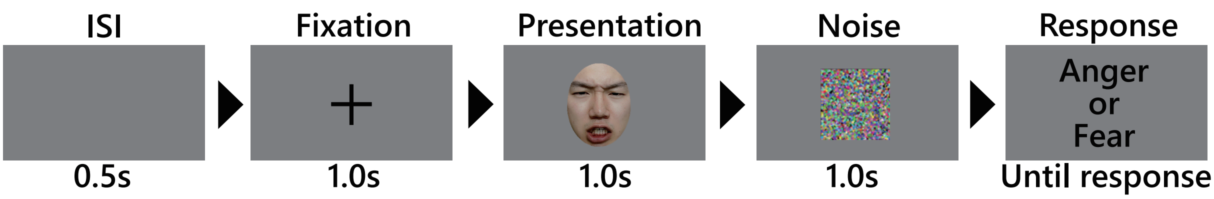

Fig. 5.2.2: Experimental procedure (Exp.1, Exp.2 & Exp.3)

Experimental procedure (Experiments 1, 2 and 3). The facial color changed during the presentation phase (1.0 s) in the facial color change conditions. Notably, the ratios of the screen to the fixation cross, facial stimulus, noise image, and text in this figure differ from the actual ratio.

Before the main session, I conducted a practice session to introduce the facial stimuli with angry or fearful expressions. In the practice session, I used the angriest (10) and the most fearful (0) faces for each sex. The facial color of the stimuli was consistently the original color (as in the OO condition), and each stimulus was assessed twice (for a total of eight trials). Feedback on correctness or incorrectness was presented on the monitor after the response only in the practice session. The practice session was established according to the results of the preliminary experiments, and the results were not used in the analysis.

Data analysis

In each condition, the rates of identification of each facial expression were fitted with a psychometric function for each participant. I used a generalized linear model with a binominal distribution in the MATLAB Palamedes Toolbox as the psychometric function (Prins, 2013, 2023; Prins and Kingdom, 2018). Before the fitting, I excluded poorly performing participants whose identification rates in the 0 (the easiest fearful face) and 10 (the easiest angry face) conditions were outside the plus and minus three sigma ranges, respectively, of the participants' averages. Three participants were accordingly excluded from the analysis. Thus, data from 19 participants were used in Experiment 1. In each condition, the point of subjective equality (PSE) for each participant was calculated from the psychometric curve. The PSE was the morphed level of facial expression at which the probability of identifying facial expression was equal for both angry and fearful faces. In this study, I focused on confirming whether facial expression judgments change depending on the presence or absence of dynamic facial color changes. Therefore, I compared the PSEs separately for two factors: the facial color change factor (facial color change vs. no-change/OR and RO vs. RR and OO) and the final-color factor (red vs. original/RR and OR vs. OO and RO). In establishing the final-color factor, I assumed that increased facial redness (OR condition) increases the perceived emotional intensity of anger and that decreased facial redness (RO condition) decreases the perceived emotional intensity of anger on the basis of reports that anger induces increased facial blood flow and causes a redder facial color (Drummond et al., 2001). Accordingly, the final-color factor was grouped into conditions expected to elicit higher/lower perceptions of anger.

For the statistical analysis, I first conducted the Shapiro-Wilk test and confirmed that the PSEs of each condition were normally distributed. I subsequently performed a repeated-measures two-way analysis of variance (ANOVA) using R 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria).

5.2.2 Results

The mean PSE for each facial color condition is shown in Figure 5.2.3. I found a significant main effect on the final-color factor ($F\left(1, 18\right) = 9.78$, $p = 0.006$, ${\eta_p}^2 = 0.352$). The post hoc test results revealed that the PSEs for the red condition (RR and OR) were smaller than those for the original condition (OO and

RO: $t\left(18\right) = -3.13$, $p = 0.006$, Cohen's $d = -0.71$). However, there were no significant main effects on the facial color change factor or interactions between factors: facial color change factor($F\left(1, 18\right) = 0.09$, $p = 0.762$, ${\eta_p}^2 = 0.005$); interaction($F\left(1, 18\right) = 0.22$, $p = 0.642$, ${\eta_p}^2 = 0.012$).

5.2.3 Discussion

These results reveal that faces whose final facial color is redder are more likely to be perceived as angry than are faces whose final facial color is consistently original. These findings contradict my hypothesis that dynamic changes in facial color affect facial expression recognition more than static facial color changes do. Moreover, the last facial color state may be an important cue for the identification of facial expressions rather than the translation of facial color. However, it has been suggested that red attracts more attention and is more strongly bound to objects in memory than green is (Kuhbandner et al., 2015). Therefore, it cannot be conclusively stated from the results of Experiment 1 that a change in facial color has no influence.

I focused on green, which is the color that is opposite red in the CIE L*a*b* color space. Angry faces with a green facial color (a*$-$) have been reported to represent reduced aggression and emotional intensity compared with the original facial color (Thorstenson and Pazda, 2021; Thorstenson et al., 2022). That is, by using a green facial complexion, it is possible to enhance the perception of anger in the original facial color, which appears relatively red. In addition, fear has been reported to be associated with decreased redness (a*$-$), yellowness (b*$-$), or both facial colors (Thorstenson et al., 2018). Research has suggested that increased facial greenness influences the perception and categorization of fear, such as increasing perceived emotional intensity, and is more likely to be categorized as fear than surprise (Thorstenson et al., 2022). Therefore, a greener color (a*$-$) was considered a useful approach for my experiment. This approach allowed us to investigate the effects of differences in facial color on the perception of emotion without relying on red, a color known to strongly influence memory. Therefore, in Experiment 2, I prepared facial stimuli with a decreased red component (a*$-$) instead of an increased red component. Next, I investigated whether the same results of Experiment 1 occurred when facial stimuli with the original facial color were observed in a relatively redder facial color.

5.3 Green vs. Original facial color (Experiment 2)

The hypothesis suggests that, if facial expression identification is influenced by dynamic changes in facial color, then the PSE for the judgment of facial expressions differs depending on the presence or absence of changes in color. However, the results of Experiment 1 revealed no significant differences

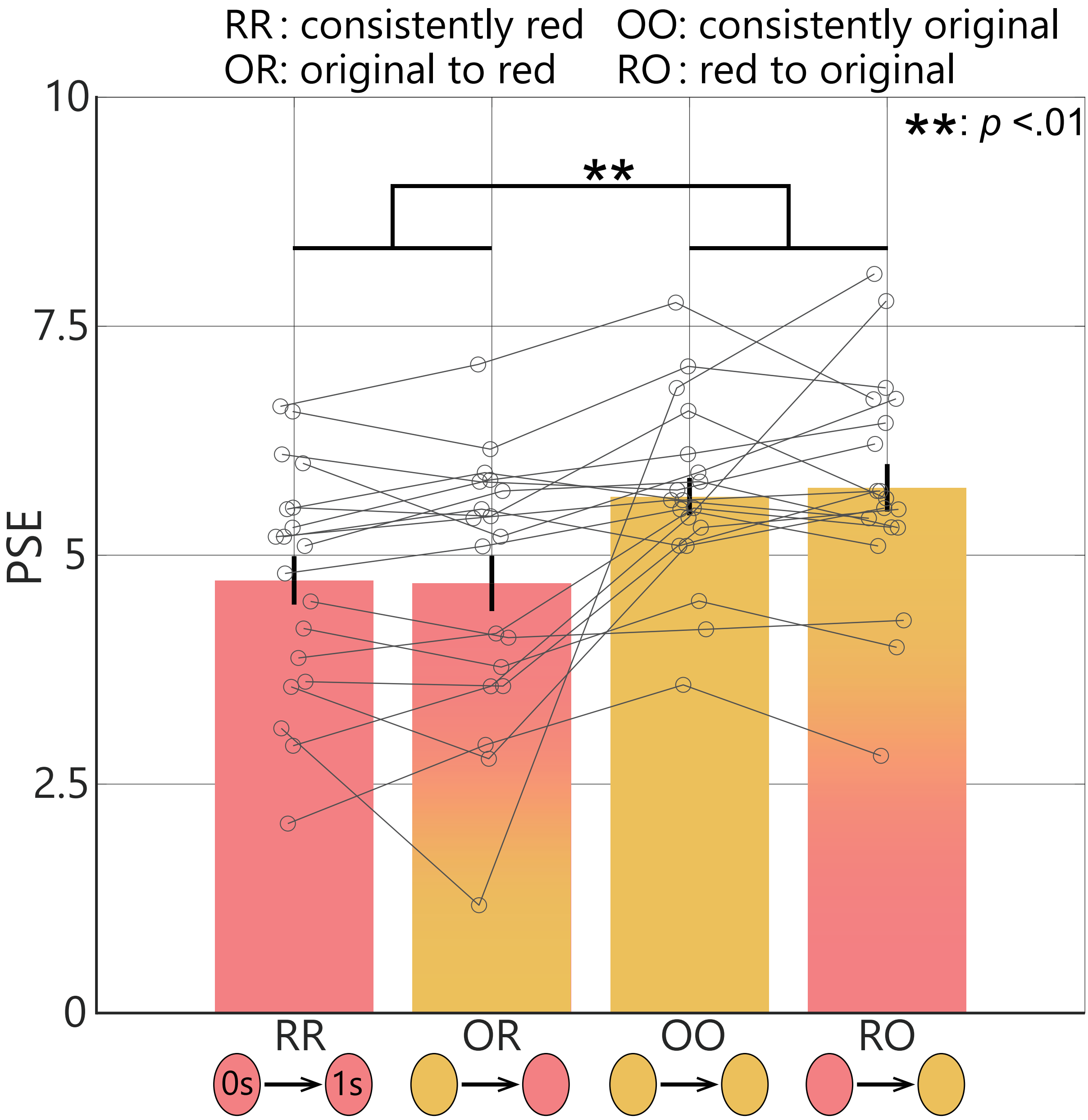

Fig. 5.2.3: Results (Exp.1)

Participants' PSE mean in Experiment 1. A smaller PSE value indicates that the participants were more likely to perceive faces in that condition as angry faces, whereas a larger value indicates that the participants were more likely to perceive faces in that condition as fearful faces. The points and lines of each gray circle signify individual data, and the error bars identify the standard error of the mean. The color below each bar in the bar graph represents the facial color at the beginning of the presentation (0 s), and the color above each bar represents the facial color at the end of the presentation (1 s).

between the changes in facial color and the no-change conditions. Possible explanations for these results include the influence of the final facial color or the effect of red, which tends to attract attention and may have diminished the effect of dynamic changes to facial color. Therefore, in Experiment 2, I conducted the same task using the color green to determine whether the results of Experiment 1 could be obtained with a reduced influence of the color red. I hypothesized that, if dynamic changes in facial color influence facial expression judgment, then reducing the effect of red should lead to a difference between the dynamic color change and no-change conditions. Conversely, if the judgment of facial expressions is influenced by the perception of the final facial color rather than by the dynamic change in facial color, then results similar to those observed in Experiment 1 are expected.

5.3.1 Materials and methods

Participants

As in Experiment 1, I recruited 22 students (10 females and 12 males; average age 22.4 $\pm$ 1.15 years, between 18 and 24 years) from Toyohashi University of Technology for Experiment 2. All of the participants had normal color vision, as verified by the same color vision test chart used in Experiment 1. The participants were fully informed about the experiment and consented to participate.

Stimuli and apparatus

The facial color states in Experiment 2 differed from those in Experiment 1. The facial color was changed from the original (a*: ± 0) to green (-12) or green to the original in the facial color change condition, whereas the color was consistently the original (± 0) or consistently green (-12) in the no-change condition (see Figure 5.3.1); I defined these conditions as “OG,” “GO,” “OO,” and “GG,” respectively. The other parameters were the same as those used in Experiment 1.

The experimental environment was the same as that of Experiment 1.

Procedure

The procedure was the same as that in Experiment 1 except that the presented facial stimuli were different.

Data analysis

Two participants’ data were excluded from the analysis by using the same criteria as those used in Experiment 1. I confirmed that the participants’ PSEs in each condition were normally distributed. The

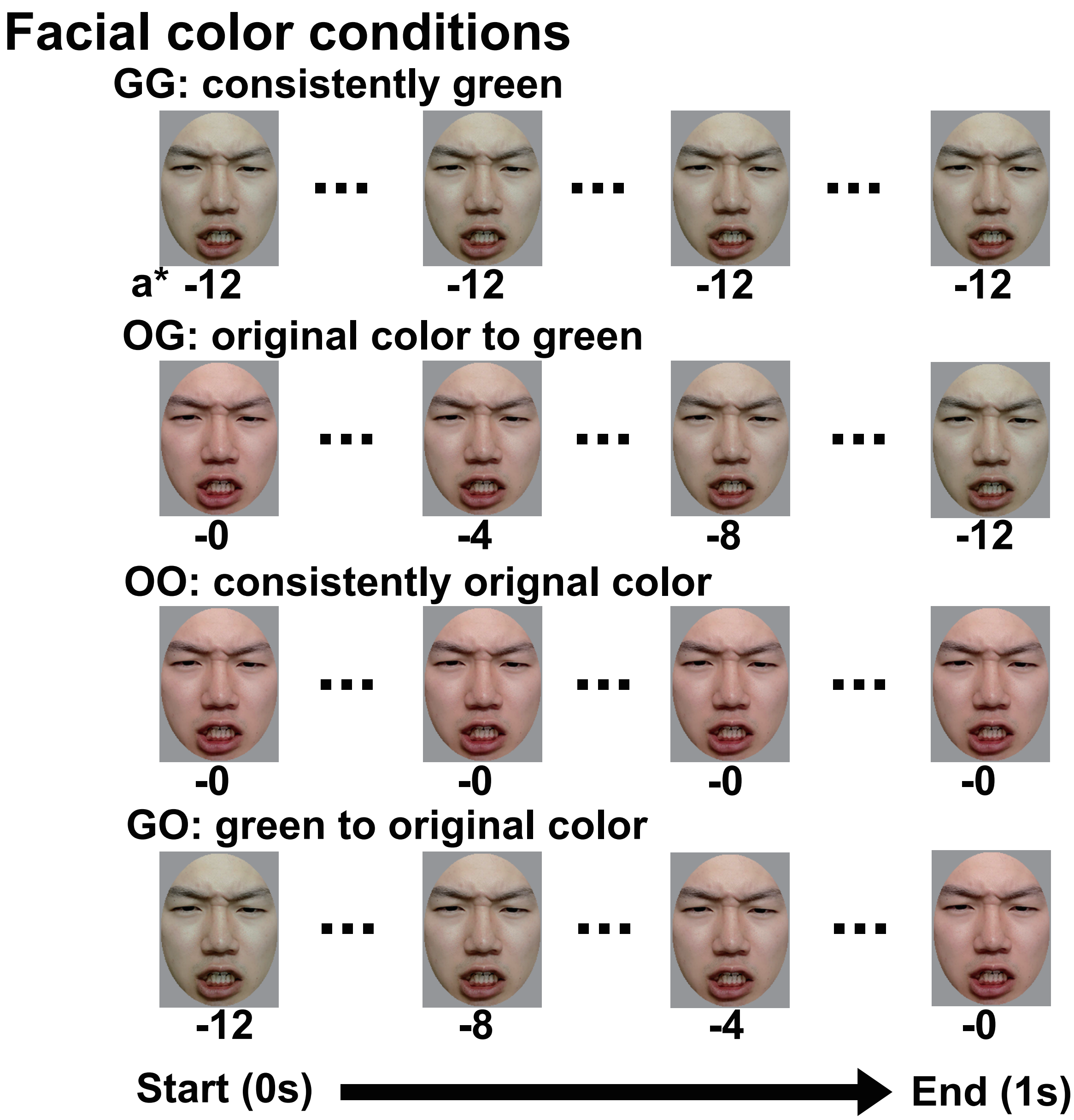

Fig. 5.3.1: Experimental stimuli (Exp.2)

Examples of the image stimuli for each facial color condition in Experiment 2.

other parameters were the same as those used in Experiment 1.

5.3.2 Results

The average PSEs for each facial color condition are shown in Figure 5.3.2. There was a significant main effect of the final-color factor($F\left(1, 19\right) = 23.84$, $p < 0.001$, ${\eta_p}^2 = 0.556$). The post hoc test revealed that the PSEs for the green conditions (OG and GG) were significantly greater than those for the original conditions (GO and OO: $t\left(19\right) = 4.88$, $p < 0.001$, Cohen's $d = 1.09$). However, similar to the results of Experiment 1, there were no significant differences between the facial color change and no-change conditions (dynamic vs. static: $F\left(1, 19\right) = 2.67$, $p = 0.119$, ${\eta_p}^2 = 0.123$), and no interactions between facial color change and the final-color factor ($F\left(1, 19\right) = 0.44$, $p = 0.514$, ${\eta_p}^2 = 0.023$). My results suggest that the participants were more likely to perceive the face for which the last facial color was the original color as angry than the face for which the last facial color was greener.

5.3.3 Discussion

My results indicate that the participants were more likely to perceive the face for which the last facial color was the original color as anger than the face for which the last facial color was green. These results suggest that the judgment of facial expression is influenced by the perception of the final facial color instead of its dynamic change. However, changes in facial color are not always linear because the speed of blood flow is nonlinear (Zonios et al., 2001). Because increased facial redness might result from increased blood flow and vasodilation, abrupt changes in blood flow might, in turn, cause rapid shifts in facial color (Drummond et al., 2001; Izikson et al., 2006). Therefore, in Experiment 3, I prepared facial stimuli with rapid facial color changes. If the final facial color plays a critical role in facial expression judgment, then I hypothesized that results similar to those observed in Experiments 1 and 2 would emerge even when the facial color change is nonlinear and rapid, and I conducted the same facial expression judgment task as in Experiment 1.

5.4 Rapid facial color change (Experiment 3)

The results of Experiments 1 and 2 suggest that the final facial color was influenced by facial expression judgments with and without dynamic facial color changes. However, changes in facial color might not be linear, as they were in Experiments 1 and 2, because the speed of blood flow is nonlinear (Zonios et al., 2001), and rapid blood flow changes might cause rapid shifts in facial color (Drummond et al., 2001; Izikson et al., 2006). Therefore, in Experiment 3, I conducted the same facial expression judgment

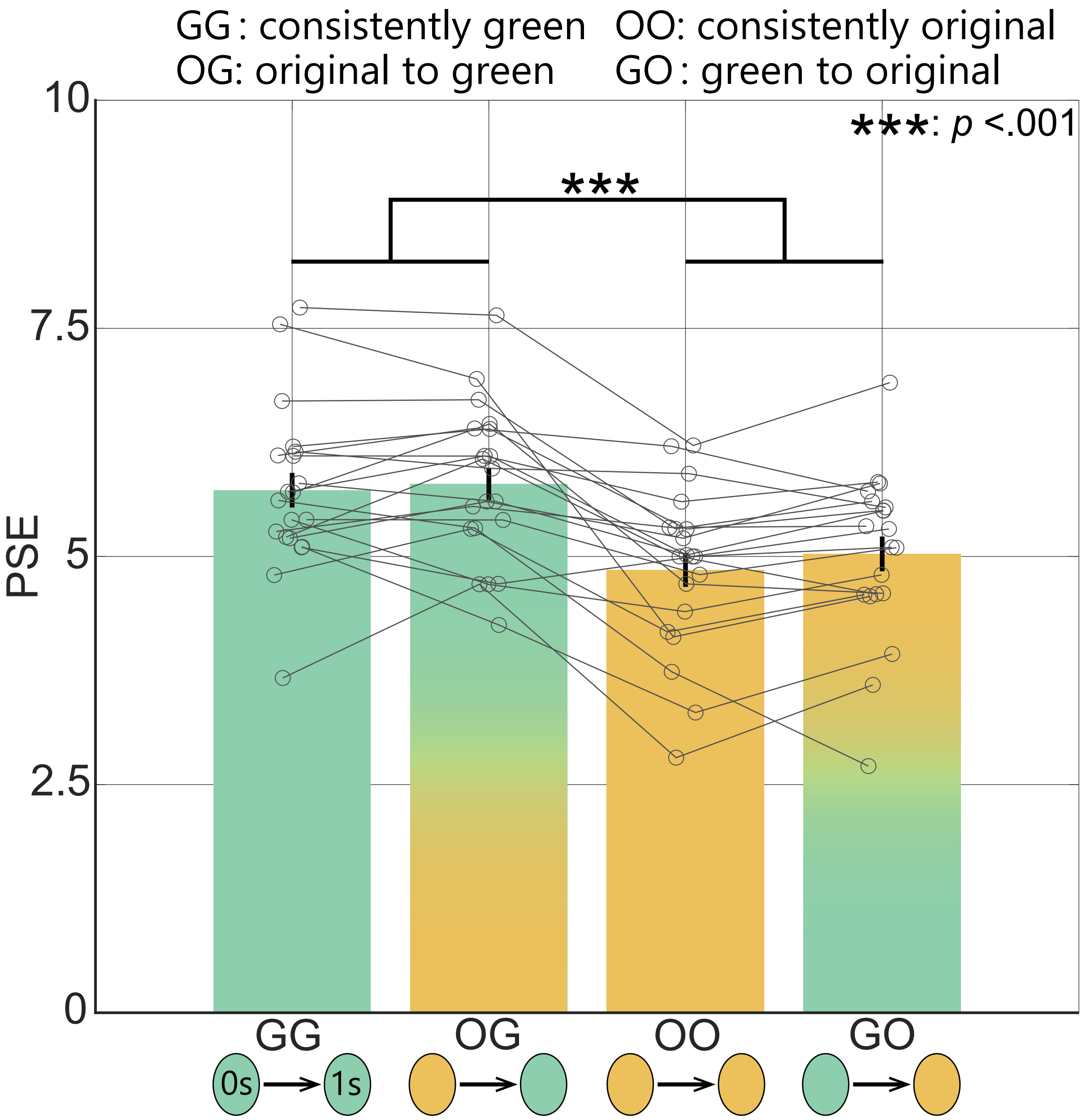

Fig. 5.3.2: Results (Exp.2)

Participants' PSE mean in Experiment 2. The other formats are the same as in Figure 5.2.3.

experiment using facial expression stimuli with nonlinear and rapid facial color changes, which were intended to reflect rapid blood flow changes and vasodilation. I hypothesized that, if the judgment of an angry facial expression is more likely with a redder final facial color instead of a rapid change in facial color to red, the results would resemble those observed in Experiment 1. Conversely, assuming that a nonlinear or rapid (more natural) facial color change plays a more important role in judging the facial expression, I predicted that facial color change would affect judgment of the facial expression more strongly than the static conditions.

5.4.1 Materials and methods

Participants

As in Experiment 1, I recruited 22 students (10 females and 12 males; average age, 21.6 ± 1.05 years, between 18 and 23 years) from Toyohashi University of Technology for Experiment 3. All of the participants had normal color vision, as verified by the same color vision test chart used in Experiment 1. The participants were fully informed about the experiment and consented to participate.

Stimuli and apparatus

In Experiment 3, the facial color transition method differed from that in Experiment 1. The facial color changed linearly from a*± 0 to 12 or 12 to ± 0 during $0.1\,\mathrm{s}$ from 0.45 to $0.55\,\mathrm{s}$, with the start of presentation at $0\,\mathrm{s}$, in the facial color change condition (see Figure 5.4.1). This color change was intended to enable rapid changes in facial color while maintaining a certain degree of naturalness. Additionally, to control (ensure consistency) the presentation duration of the facial color state within each facial color change condition, I adopted this color change method and avoided situations in which colors closer to the original color state in the red-to-original facial color change condition were presented for longer durations. Each condition was defined as “rOR” (rapid: original to red) or “rRO.” The no-change condition was the same as that used in Experiment 1 (“OO” and “RR” conditions).

The experimental environment was the same as that of Experiment 1.

Procedure

The procedure was the same as that in Experiment 1 except that the presented facial stimuli were different.

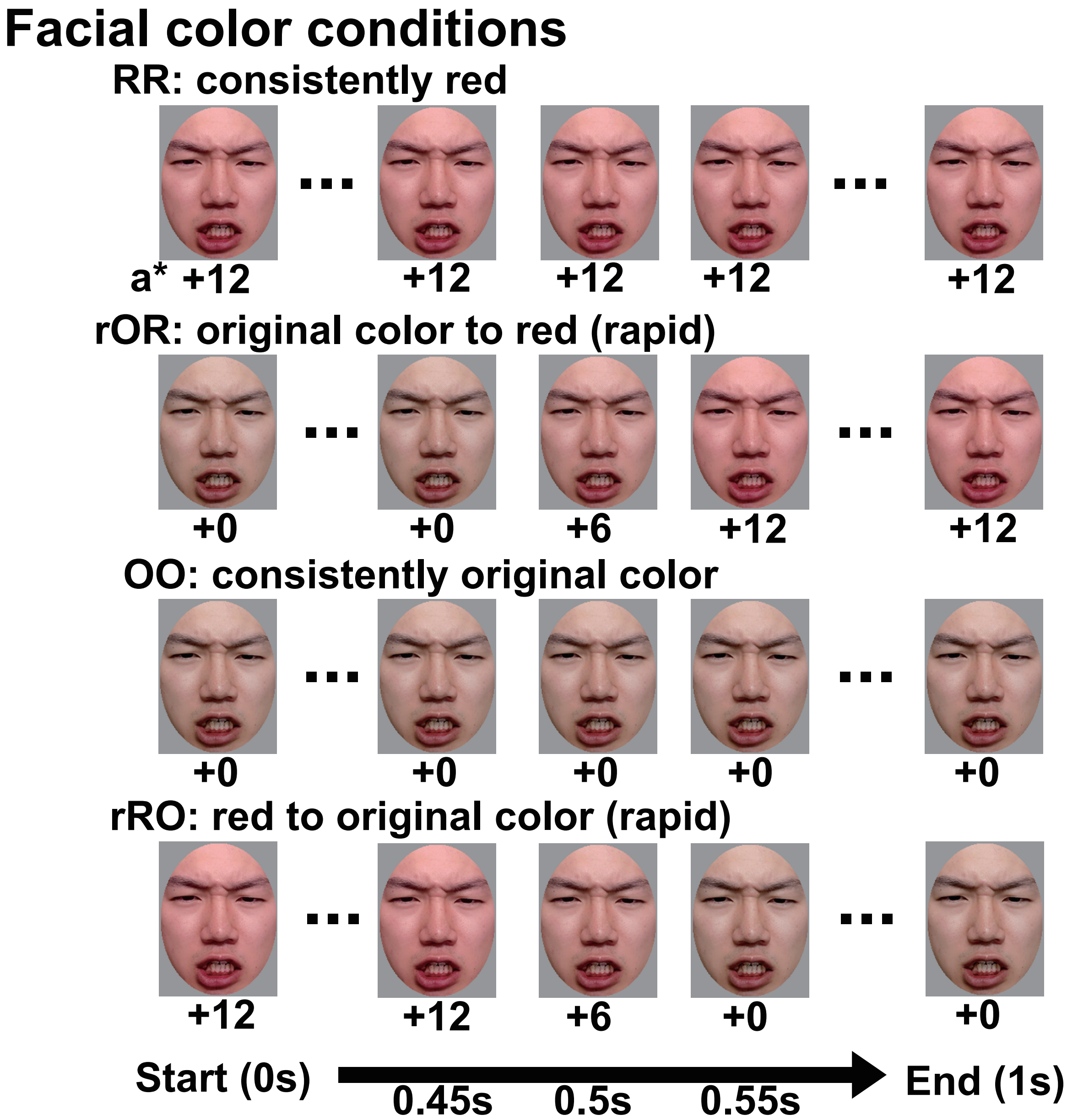

Fig. 5.4.1: Experimental stimuli (Exp.3)

Examples of the image stimuli for each facial color condition in Experiment 3.

Data analysis

One participant's data were excluded from the analysis by using the same criteria as in Experiment 1. I performed a nonparametric test with the R package nparLD (Noguchi et al., 2012), because the participants' PSE data were not normally distributed. ANOVA-type statistics (ATS) were calculated via nonparametric tests. Post hoc tests were performed with the Wilcoxon test. The other factors were the same as those in Experiment 1.

5.4.2 Results

The average PSEs for each facial color condition are shown in Figure 5.4.2. I found a significant main effect of the final-color factor($ATS\left(1\right) = 19.43$, $p < 0.001$). As a result of the post hoc test, I observed that the PSEs for the red condition (RR and rOR) were significantly smaller than those for the original condition (OO and rRO: $Z\left(20\right) = -3.59$, $p < 0.001$, $r = -0.79$). However, similar to the results of Experiments 1 and 2, there were no significant differences between the facial color change and no-change conditions (dynamic vs. static: $ATS\left(1\right) = 0.28$, $p = 0.595$), and there was no interaction between facial color change and the final-color factors($ATS\left(1\right) = 0.02$, $p = 0.890$).

5.4.3 Discussion

My findings suggest that the final facial color state may be a more important cue for judging facial expression than the facial color transition.

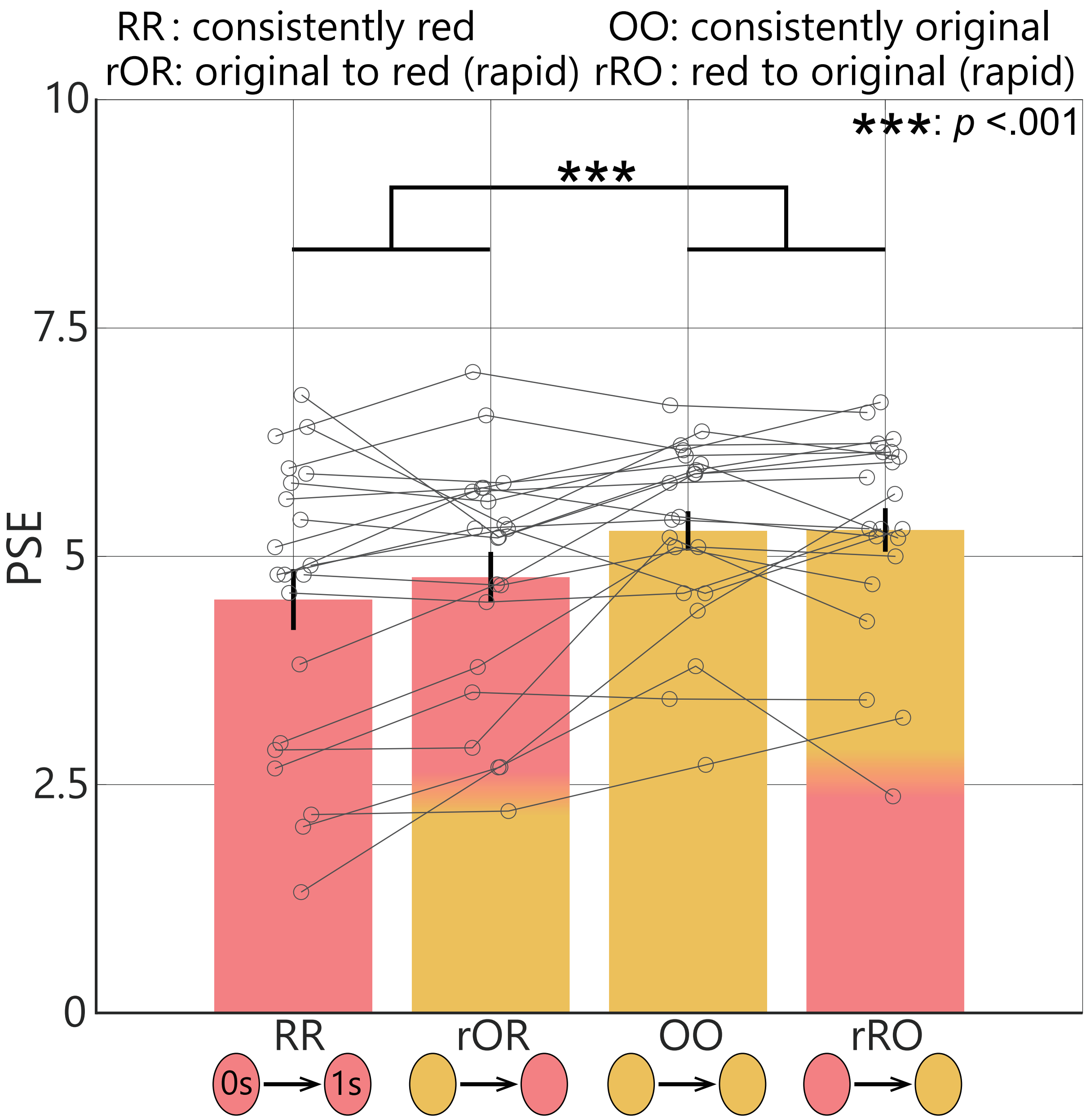

Fig. 5.4.2: Results (Exp.3)

Participants' PSE mean in Experiment 3. The other formats are the same as in Figure 5.2.3.

5.5 General discussion of this chapter

In this study, a facial expression judgment task was performed in which different facial color conditions were used to investigate the effects of dynamic changes in facial color on the identification of facial expressions. The results of Experiments 1, 2, and 3 revealed no significant differences between the dynamic change and static facial color conditions. However, a relatively reddish final facial color was likely to be perceived as an angry face. Humans' retrospective evaluation of experiences and memories is heavily influenced by the peak (most intense) moment and the end (final) moment instead of the overall average or duration (Alaybek et al., 2022; Fredrickson and Kahneman, 1993; Horwitz et al., 2024; Hsu et al., 2018; Kahneman et al., 1993). Therefore, the participants might have used the final facial color instead of facial color changes as a cue for facial expression judgment. My results suggest that facial expression identification is affected by the ultimate color rather than by the processing of changes in facial color. In addition, although the method and speed of facial color change differed between Experiments 1 and 3, the facial color changes (dynamic vs. static) did not affect facial expression judgment. These results show that, compared with linear and rapid dynamic facial color changes, the final facial color state plays a more important role in promoting facial expression perception of anger. As suggested in Chapter 4, the interaction between anger and red enhances brain wave activity associated with threat-related processes. Therefore, it is possible that the final state conveying threat-related information, such as the terminal facial color, was processed preferentially over the dynamic change process, thereby exerting a dominant influence on judgments of facial expression (anger).

Although previous studies have reported that dynamic facial expression changes influence emotion judgment (Ambadar et al., 2005; Fujimura and Suzuki, 2010), my results indicate that, compared with static conditions, dynamic facial color changes do not significantly affect emotion judgment. Given that prior evidence suggests that the right hemisphere predominantly contributes to facial expression processing, whereas the left hemisphere is more involved in the perception of facial color (Killgore and Yurgelun-Todd, 2007; Najt et al., 2012; Nakajima et al., 2012, 2014), it is plausible that the neural mechanisms involved in facial expression processing are distinct from those involved in facial color processing. Consequently, I infer that the contribution of dynamic facial color change to facial expression judgment is relatively limited compared with that of dynamic facial expression change.

In this study, the perception of anger increased with a reddish facial color (Experiments 1 and 3) and decreased with a greenish facial color (Experiment 2). These results are similar to those of previous studies that revealed that the relationship between facial expression and color modulates human perception and response (Kato et al., 2022; Minami et al., 2018; Nakajima et al., 2017; Nguyen et al., 2023; Peromaa and Olkkonen, 2019; Thorstenson et al., 2022, 2021). These findings align with the results of Nakajima et al. (2017) and Minami et al. (2018), who reported that a redder facial color (a*+12) enhanced the perception of anger in a facial expression judgment task in which faces that were morphed from fearful to angry facial expressions were used. My findings are also consistent with those of previous studies in which reddish faces increased the categorization of anger, whereas a green facial color decreased it (Nakajima et al., 2017; Thorstenson et al., 2022). My results support the idea that a reddish facial color increases people's perception of anger. In addition, reddish angry faces increase the perception of emotional intensity, aggression, and dominance, whereas greenish angry faces decrease these perceptions (Thorstenson et al., 2022, 2021). The results of this study can be attributed to these changes in the recognition of angry faces due to facial color.

In my experiments, the perception of anger tended to decrease when the facial color shifted dynamically in the opposite color direction to red (RO, red to original condition in Experiment 1; OG, original to green condition in Experiment 2). These results suggest that facial expression judgment is influenced by the last facial color even when a relatively reddish facial stimulus, which is more likely to be perceived as an angry face, is initially presented. Studies have reported that a redder facial color increases the emotional intensity of anger, whereas a greener facial color decreases it (Thorstenson et al., 2022). My findings on the effects of dynamically decreasing facial color may provide new insights into the relationship between facial expression recognition and color, suggesting that the final emotion intensity takes precedence over the maximum emotional intensity in facial expression judgment. In particular, a previous study indicated that dynamically increasing facial color in the emotion-associated color direction enhances perceived emotional intensity (Thorstenson et al., 2021). In contrast, the dynamic decrease in facial color observed in this study suggests the possibility of reducing perceived emotional intensity. However, there was a relatively large change in facial color because the change in this study was a*12 or -12 within 1 s, whereas in the experiment by Thorstenson et al. (2022), it was a* and b* 5 or -5 within 1 s. Therefore, considering that the results of this study are limited in scope is reasonable.

In this study, I found that the perception of anger was lower for greenish faces than for the original facial color (green vs. original; Experiment 2). Most previous studies have compared differences in the perception of facial expressions by using red, the original facial color, and blue (red vs. original vs. blue; Nakajima et al., 2017) or have compared red and green (red vs. green) or red, the original facial color, and green (red vs. original vs. green; Thorstenson and Pazda, 2021), whereas a few studies have explored the use of relative redness or compared the original color and green. My findings suggest that the judgment of facial expression is influenced by even relatively reddish facial colors, such as combinations of original and greener colors. These findings provide new evidence that supports the role of perceptual responses in the relationship between facial expression and color. In particular, perceptions of facial expression as depicting anger or fear may be modulated not by the deviation in the absolute color from the original facial color (e.g., redder or greener than the original color) but by how red the face is relative to the other faces both within a trial and between trials (that is, within a block).

The limitations of this study that should be addressed in future research are as follows. First, because this study focused on the differences between dynamic changes in facial color and static facial color, the presence or absence of perceived changes in facial color was prioritized as a key factor. On the basis of previous studies, I adopted simple parameters for the amount and color direction of facial color change (a*±12; Nakajima et al., 2017; Thorstenson et al., 2021). However, facial color changes in nature are not uniform (Jimenez et al., 2010; Kikuchi et al., 2015; Moretti et al., 1959). It has been reported that, when individuals express anger, facial blood flow increases, causing the face to appear redder (Drummond, 1999; Drummond et al., 2001; Kreibig, 2010). However, this color change is not influenced by a single hue alone (not only a* channel) but also by the colors inherent in substances such as hemoglobin and melanin, which are included in blood flow (Edwards and Duntley, 1939; Kikuchi et al., 2015; Zonios et al., 2001). In addition, because of variations in the thickness and blood vessel distribution of facial skin, facial color changes do not necessarily occur with the spatial uniformity observed in the experiments of this study (Moretti et al., 1959; Tsumura et al., 1999, 2003). Experiments that use facial color manipulation related to components of hemoglobin or melanin (e.g.,Kato et al., 2022) should be conducted in the future.

Second, the effects of color may have been strong. As previously explained, the parameters of a* in this experiment were set on the basis of prior research by Nakajima et al. (2017), but the amount of color change was relatively large. Thus, it is possible that the effect of dynamic facial color changes was overshadowed by the saliency of the color.

6 | Conclusion

This thesis examined how the semantic congruency between facial expression and facial color modulates cognitive processing, and aimed to determine whether such modulation occurs even under unintentional bias conditions. To address this research question, this study focused on memory color effects (Chapter 3) and selective attention (Chapter 4), examining differences in color memory and EEG activity associated with top-down processing across combinations of facial expressions and facial colors. In addition, by investigating the influence of contextual information induced by dynamic changes in facial color, this thesis further substantiated the notion of judgment modulation driven by the semantic congruency between facial expression and color (Chapter 5).

6.1 Summary

Effect of facial expression on memory color of facial color

In Chapter 3 the memory color effect on facial expression was examined: does the semantic color memory of faces differ depending on facial expression? To investigate this question, I examined whether the memory color effect for faces varies depending on facial expression. Specifically, I estimated the subjective achromatic point for facial expression stimuli and compared its deviation from the physical achromatic point across expression conditions. I hypothesized that if memory representations of facial color are shaped by expression-related color associations (e.g., anger linked to warmer tones, fear to cooler tones), then the subjective achromatic points would vary with facial expression.

In Experiment 1, I conducted color adjustment task that participants were asked to adjust the color of facial expression stimuli (anger, neutral, and fear) and a banana stimulus to be achromatic. As the results of Experiment 1, there were no significant differences in the subjective achromatic point between facial expressions, and suggested that the range of participant's achromatic perception expanded by chromatic adaptation. In Experiment 2, I conducted color selection task with accounting the chromatic adaptation and human's color sensitivity of face. Participants were asked to select, from two alternatives, the color that they perceived as corresponding to the facial color of the presented facial expression stimulus. The results showed that the memory color effects of faces differed depending on facial expressions due to the subjective achromatic points of angry and fearful faces significantly shifted toward the opposite color direction compared with neutral faces. This research suggests that the memory color of faces differs depending on facial expressions and the semantic congruency between facial expression and color, such as angry and red, affects the memory color.

The interaction between facial expression and color modulates brain activity reflects selective attention

In Chapter 4 EEG modulation by facial expression and color was examined: is the EEG component associated with selective attention modulated by the interaction between facial expression and color? To investigate this question, I analyzed whether ERP P3 amplitudes for faces vary depending on facial expression and color by recording EEG data. I hypothesized that if semantic congruency between facial expression and color, especially anger and red, modulates top-down processing (i.e., selective attention) ERP P3 would also be modulated by the interaction.

In the experiment, an oddball paradigm was conducted in which facial expression (angry, neutral) and facial color (original, red, green) were systematically combined. The results were found that the P3 amplitude difference between target and standard stimuli was modulated by the combination of facial expression and color. Specifically, reddish angry faces elicited larger P3 amplitudes than reddish neutral faces. In addition, there were no interactions between facial expression and color on P1 and both sides N170 components. These findings suggested that the semantic congruency between facial expression and color appears in later cognitive processing stage, rather than the processing stages associated with facial expression or color alone. In this research, the influences of top-down processing induced by semantic congruency between facial expression and color was also observed in EEG activity.

The effect of terminal color dominance in expression recognition

In Chapter 5 the effect of color change direction on facial judgment was examined: does the direction of facial color change (i.e., the terminal color) modulate facial expression judgments, even when the total perceived amount of color is constant? Although previous studies have typically employed facial expression stimuli with static facial colors, this study used stimuli with dynamic facial color changes to address this research question. It was hypothesized that if facial expression cognition is modulated by acquired knowledge derived from one's own experiences, then facial expression judgments would vary depending on the direction of facial color change, even when the total perceived amount of color remains constant. Furthermore, it was predicted that dynamic facial color change conditions, which more closely resemble natural situations, would be more susceptible to knowledge-based biases than static facial color conditions.

Across three experiments, facial expression judgment tasks were conducted using facial expression morphed stimuli from fear to anger. Experiment 1 employed red and original facial colors, Experiment 2 used green and original facial colors, and Experiment 3 designed rapid facial color changes conditions to simulate the non-linear facial color change. In all experiments, faces with relatively redder terminal colors were more likely to be perceived as angry, even when facial shape condition was same. However, no significant differences were observed between dynamic change and static of facial color conditions. These results indicated that the facial expression judgments were modulated by the direction of facial color change, whereas the presence or absence of dynamic facial color changes in semantic congruency might have little effect on the modulation of facial expression judgments. Rather, it was shown that the terminal facial colors play the important role for facial expression recognition. This suggested the possibility that threat-related information in the final state, such as the terminal facial color, was prioritized over the dynamic change process and exerted a dominant influence on anger judgments.

6.2 General discussion

The findings of this study indicated that modulation driven by the semantic congruency between facial expression and color was observed even during unintentional cognitive processing (Chapters 3 and 4). These results suggested that the bias effect induced by such semantic congruency influences cognitive processing stages from perception to judgment, rather than directly affecting judgments or responses themselves. In particular, these findings suggest that knowledge related to the semantic congruency between anger and red does not influence behavioral responses merely as a judgmental strategy, but instead operates as a top-down process, such as cognitive processing related to memory or threat, that modulates perception and evaluation themselves. These findings are are consistent with previous research reporting that contextual information influences facial expression recognition and that brain activity is modulated by unnatural or incongruent facial color (Righart and De Gelder, 2008; Xu et al., 2017; Nakajima et al., 2012, 2014). Moreover, even for implicit facial expressions that are difficult to categorize, perceived interpersonal closeness varied as a function of facial color, suggesting that contextual congruency between facial expression and color can influence not only explicit judgments but also cognitive processing and social evaluations (Nguyen et al., 2023).

Furthermore, as shown in the results of Chapter 5, even when the total perceived amount of color (i.e., the overall duration of color perception) was equivalent, the perceived facial expression varied depending on the direction of color change; faces that changed toward a reddish tone were more likely to be perceived as expressing anger. Taken together, these findings also suggested that the observed effects could not be explained merely by a simple response bias such as "the face is angry because color is red," but rather reflect cognitive and judgmental modulation through top-down processes driven by the semantic congruency between facial expression and color. However, because no significant difference was observed between the dynamic and static conditions, the facilitative effect of dynamic change factors on the processing of semantic congruency between facial expression and color may be very weak when facial color is presented in isolation. Rather, the dynamic change of both facial expression and facial color might be required to produce response enhancement driven by dynamic change factors. This interpretation aligns with the findings in Chapter 4, where no interaction was observed in ERP components related to facial expression or facial color alone, whereas an interaction emerged in components reflecting semantic congruency.

Therefore, this thesis proposes a model of cognitive modulation driven by the semantic congruency between facial expression and facial color, as illustrated in Figure 6.2.1. Humans empirically perceive, memorize, and learn associations between facial expressions and colors through various experiences, such as physiological reddening caused by arousal, expressive representations in animation, and associative imagery. Through these experiences, individuals form knowledge about the semantic congruency between facial expressions and facial color, including memory color. This knowledge does not directly bias responses; rather, it influences cognitive processing as a top-down mechanism that follows facial (expression) perception, thereby leading to response modulation driven by the interaction between facial expression and color.

This model is also expected to be applicable not only to the relationship between facial expression and color but also to aspects such as color perception, skin texture perception and so on. For example, memory color is formed from one's experience with the color of objects, and shifts the perceived color of the object toward its typical color (Witzel and Gegenfurtner, 2013). In the facial color perception, Hasantash et al. (2019) reported that in a color-matching task using stimuli illuminated by low-pressure sodium light, which renders scenes monochromatic, participants perceived facial color as sickly and matched it toward green. They further reported that this color-matching toward green did not occur for isolated skin patches with facial features occluded or for fruit stimuli. They suggested that when retinal color mechanisms are impaired, humans rely on memory, which in turn modulates color perception

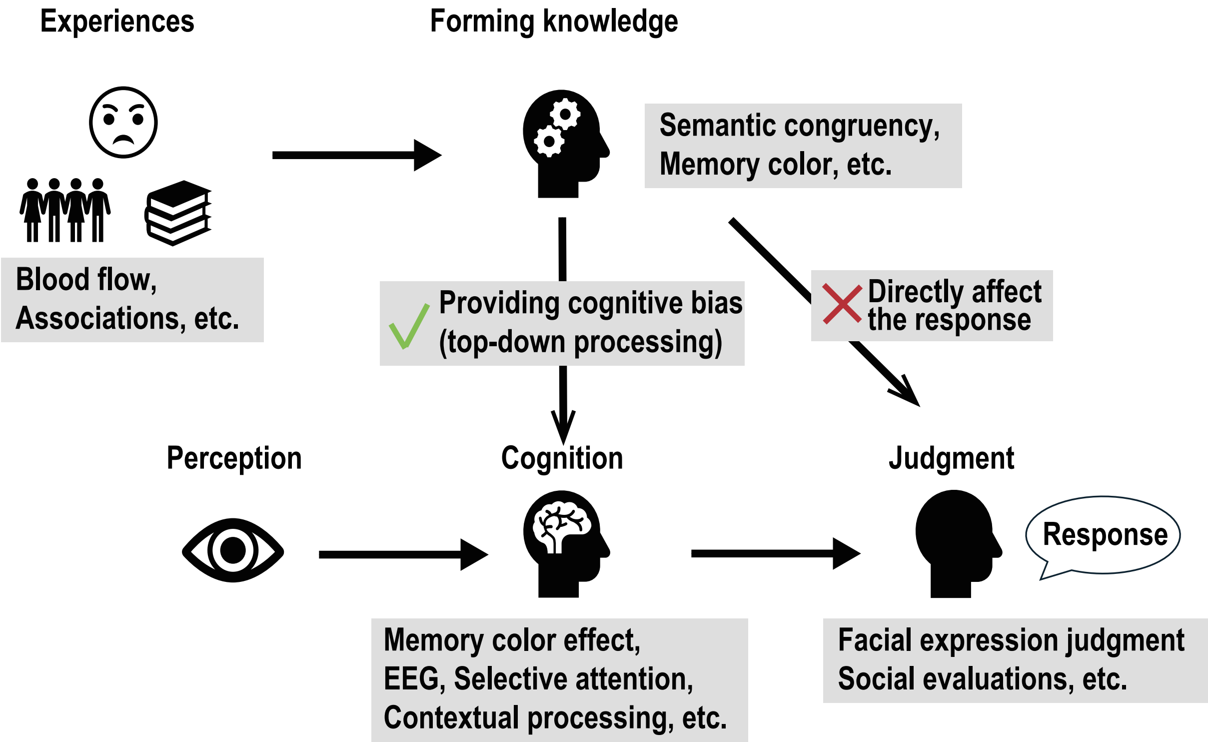

Fig. 6.2.1: Overview of the proposed model

Knowledge is formed from information acquired through one's own experience. This formed knowledge affects cognitive processing and modulates responses (judgments) to perceived stimuli, rather than directly influencing responses.

toward a green facial color (Hasantash et al., 2019). As an example from the perception of skin texture, it has been shown that the perceived moisture of skin decreases when rating skin image stimuli with white streak-like markings (skin images which enhanced the high-spatial-frequency components of skin lightness; Hasegawa et al., 2025). In reality, when the skin becomes dry, white streaks appear on its surface. Thus, humans might evaluate skin moisture or dryness based on such physiological knowledge and visual cues such as shape and color.

These studies are also similar to my idea suggesting that empirically acquired knowledge can influence cognitive processing and, in turn, modulate responses. Thus, the proposed model of cognitive modulation may extend beyond facial expression and color, offering a framework for understanding how knowledge and memory influence responses and judgments.

Moreover, my studies can also be regarded as an extension of previous studies that focused on the content of the facial stimuli (e.g., Nakajima et al., 2017; Thorstenson and Pazda, 2021), examined from the perspective of cognitive memory. My findings showed that memory colors associated with angry faces, as well as the corresponding memory color effects, differ from those associated with neutral faces, suggesting that the association between anger and red also influences long-term memory (Chapter 3). In addition, in short-term memory, I found that combinations of anger and red contributed to working memory updating, as reflected in increased ERP P3 (Chapter 4). Furthermore, the terminal facial color plays an important role on facial expression recognition (Chapter 5). Therefore, the present study extends previous studies on perceptual modulation of anger and red from a temporal framework, suggesting that modulation driven by the semantic congruency between anger and red is not limited to momentary judgments but also affects memory-related processes.

The limitations of this thesis that should be examined in future research are as follows. First, this study did not investigate demographic characteristics. Knowledge and experiences are acquired over the course of development. In addition, it has been reported that both the number and strength of associations between emotions and colors vary across different age groups (Terwogt and Hoeksma, 1995; Jonauskaite et al., 2024). Therefore, it is necessary to conduct experiments involving participants across a wide range of ages and developmental stages to evaluate the validity of the proposed model.

Second, all of the participants in all of my experiments were Japanese or familiar with Japanese culture. Moreover, the Japanese facial images were employed as experimental stimuli. Therefore, due to it has been suggested that the judgment of facial color is based on the average skin tone observed in daily life, the findings of this study should be interpreted as being based on phenomena observed under specific conditions, and their validity is likely to be limited to particular populations (Shimakura and Sakata, 2022). However, it has been consistently reported that anger is the emotion associated with the color red in many countries (Jonauskaite et al., 2020). In addition, Tiippana et al. (2025) reported no significant difference in the neutral facial point between Finnish and Japanese participants in a task in which they adjusted facial expressions to neutral under different background color conditions. Thus, influences of cross-culture might have had less of an effect on my results.

Third, I did not investigate the brain activity patterns and regions at cognitive processing. It has been reported that brain regions involved in facial processing and memory that could not be measured solely through EEG, such as the fusiform face area (FFA) for face perception, the amygdala for facial expression processing, and the hippocampus for memory (e.g., Nakajima et al., 2014; Richter-Levin and Akirav, 2000; Bird and Burgess, 2008). Therefore, future research could lead to more advanced and comprehensive discussions, by employing neuroimaging techniques such as fMRI to investigate differences in brain activation regions and activity patterns associated with variations in facial expressions and colors.

Fourth, the experiments in this study were restricted to the combination of anger and red, which showed a salient response in previous studies. However, it is plausible that comparable effects might also emerge from other pairings of facial expressions and color such as happiness and yellow, sadness and blue. In previous studies, it has been reported that the accuracy of emotion categorization was enhanced by facial color which associated with facial expressions, and the perceived emotion intensity also increased depending on the combination of facial expression and facial color (Thorstenson et al., 2022, 2021). Based on these findings, it would be appropriate to conduct further studies employing other combinations of facial expressions and facial colors in order to allow for a more comprehensive discussion of the model.

Fifth, this study did not target physiological changes in facial color. In my experiments, I manipulated either the original colors of facial photographs or added a uniform red coloration. However, facial color in natural settings varies as a function of physiological processes such as changes in blood flow, and the magnitude of these changes differs across facial regions (Edwards and Duntley, 1939; Kikuchi et al., 2015; Zonios et al., 2001; Kreibig, 2010). Therefore, the present findings and suggestions are limited to the semantic congruency between anger and red, and additional studies are required to examine physiological congruency from a biological perspective.

Finally, the individual characteristics of the participants were not researched in this experiment. The ability to detect faces, recognize or process facial expressions, and bias attention toward facial expressions such as angry faces varies depending on trait anxiety, autism spectrum disorder, or moebius syndrome (Golarai et al., 2006; Surcinelli et al., 2006; Telzer et al., 2008; Tanaka and Sung, 2016; Quettier et al., 2023). Therefore, the individual characteristics of participants possibly may have affected differences in attention to facial expressions, and the differences in the magnitude of effects due to individual characteristics must be examined in the future.

Publication List

List of Papers with Referee's Review

First-authored

- Yuya Hasegawa, Hideki Tamura, Shigeki Nakauchi & Tetsuto Minami. "Interaction between Facial Expression and Color in Modulating ERP P3." *eNeuro*, 12(1), ENEURO.0419-24.2024, 2025. https://doi.org/10.1523/ENEURO.0419-24.2024
- Yuya Hasegawa, Hideki Tamura, Shigeki Nakauchi & Tetsuto Minami. "Facial expressions affect the memory of facial colors." *Journal of Vision*, 24(5):14, 2024. https://doi.org/10.1167/jov.24.5.14

Co-first-authored

- Miku Shibusawa, Yuya Hasegawa, Hideki Tamura, Shigeki Nakauchi & Tetsuto Minami. "Dynamic versus static facial color changes: Evidence for terminal color dominance in expression recognition." *Journal of Vision*, 25(12):8, 2025. https://doi.org/10.1167/jov.25.12.8
- Yuya Hasegawa, Hideki Tamura, Tama Kanematsu, Yuzuka Yamada, Yohei Ishiguro, Shigeki Nakauchi & Tetsuto Minami. "Visual cues for moisture perception of facial skin: a pilot study on the effects of enhancing high-spatial-frequency components of skin lightness to decrease perceived moisture levels in young Asian observers." *Journal of the Optical Society of America A*, 42, B23–B33, 2025. https://doi.org/10.1364/JOSAA.536898

List of Papers at International Conference with Referee's Review

First-authored

- Yuya Hasegawa, Hideki Tamura, Shigeki Nakauchi & Tetsuto Minami. "The relationship between facial expression and color: Investigating their interaction in selective attention using event-related potentials" *European Conference on Visual Perception (ECVP) 2025*, Mainz, Germany, August 24–28, 2025.
- Yuya Hasegawa, Hideki Tamura, Shigeki Nakauchi & Tetsuto Minami. "Do facial expressions affect the memory of facial color in an achromatic color adjustment task?" *European Conference on Visual Perception (ECVP) 2023*, Paphos, Cyprus, August 27–31, 2023.

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