Early-Stage Neural Processing Reveals Distinctive Responses to Saliency-Differentiated Colors in Various Types of Color Vision

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Abstract: People with protan or deutan color vision are expected to have reduced chromatic sensitivity on the red-green color axis due to altered cone sensitivities; however, complemented sensitivities have been reported in some studies. The mechanism involved in the enhanced sensitivity is considered to encompass a broad spectrum of psychophysiological processes. Nonetheless, the specific details remain unknown. This study investigated the differences in attention-related neural activities between common trichromats and deuteranomalous trichromats during the observation of chromatically identical colors that differ in saliency. Global field power and event-related potentials were analyzed to elucidate how higher cognitive process, particularly attention, manifests in the temporal domain of neural processes in response to stimuli saliency, across color vision types. The finding revealed increased neural activity toward less salient color stimuli in both color vision groups, reflecting a heightened attentional level. Notably, distinct activity patterns were observed at different time frames: common trichromats exhibited at later positive component (P3), and deuteranomalous trichromats exhibited at earlier positive component (P2). Surprisingly, despite their diminished chromatic sensitivity, deuteranomalous trichromats responded quicker to the saliency differences. The result suggests that temporal characteristics play a crucial role in complementary mechanisms in chromatic sensitivities in individuals with diverse color vision.

1. Introduction

Due to the genetic mutation, there are about 5 – 8 Based on the way of deviation in cone sensitivity from the common types, human color vision can be categorized into a few types. The most prevailing color vision type is called common trichromacy, in which three classes of photosensitive cells—L, M, and S cones—in the retina are excited by long-, middle-, and short-wavelength visible spectrum light, respectively. In trichromatic vision, signals produced by these cells are processed to organize color experience in terms of two opposing color axes, red-green and blue-yellow, produced by M versus L cone contrast and S versus M + L cone contrast, respectively [1–3]. Anomalous trichromacy, a variant type of trichromacy, is reported to have a high prevalence, occurring in approximately 6% of Caucasian males [4]. It is characterized by a sensitivity shift in either M or L cone cells due to variations in the visual pigment genes responsible for their wavelength sensitivity [5]. Differences in the extent of the shift in anomalous trichromacy brings about diverse perceptual differences [6]. Complete replacement between M and L cone cells also occurs, but is much less prevalent, affecting approximately 2 % of males [4]. Such color vision types, with either a combination of M and S cone cells (protanopia) or L and S cone cells (deuteranopia), are classified as subtypes of dichromacy, and the color experience of those individuals is generally thought to be represented only by the blue-yellow axis due to the reduction in number of classes in cone cells from three to two. Tritanopic dichromacy—with M and L cells—and monochromacy—with S cells or no functional cone cells—are rare in the human population [5]. Although human color vision types can be mainly classified into the categories described above, continuous

perceptual differences within each type, especially in anomalous trichromacy, obscure the borders between types. Any sensitivity shift or loss affecting cone cells reduces sensitivity in color discrimination in the corresponding area of the visible light spectrum. However, as stated earlier, actual color discrimination of sensitivity-altered individuals does not always align with the estimated color perception based on their specific cone sensitivities. Protanopes and deuteranopes, i.e., dichromats with a combination of S and M cone cells or S and L cone cells, respectively, are expected to have a degree of blue-yellow color perception mediated by neutral gray in the middle, but not red-green color discrimination. However, despite the absence of an effective red-green contrast mechanism, several studies have shown that they demonstrate some degree of red-green discrimination [7–10]. One such study involved a color-naming experiment in which dichromats and trichromats showed common color categories and performed similarly in naming basic color terms [11], including red and green, when the color stimuli were presented in a large visual field with an adequate period of time to identify their names [12].

Similarly, when the use of basic color terms by protanopes and deuteranopes was modeled based on empirically acquired data, the results were better explained when it was assumed that they were capable of residual red-green discrimination in addition to processing blue-yellow and light information [13, 14]. Furthermore, [15] recently provided additional evidence for post-receptoral amplification of red-green processing signals by anomalous trichromats in a psychophysical experiment. Several possible mechanisms have been suggested to explain the enhanced discrimination of colors on the red-green axis by anomalous trichromats and dichromats: rod contribution providing alternative signals [8, 9, 16]; enhancement of S cone sensitivity in long-wavelength regions serving as alternative signals [7]; and variation in optical density [10, 17]. Another recent study reported that neural input from cone cells with reduced wavelength sensitivity was amplified at the post-receptoral stage in the early visual cortex of the V2 and V3 areas in anomalous trichromats [18].

These studies suggest the idea that both anomalous trichromats and dichromats somehow compensate for their reduced wavelength sensitivity through neural processing to attain a perceptual experience somewhat similar to that of common trichromats. This enhanced perception may be acquired based on learnt perceptual differences from common trichromats or as the result of optimized neural processes based on their possessed sensitivities in relation to preferred perceptual experience in a given physical environment. Either way, there seems to be some difference in the mechanism of color perception between common trichromats and individuals with altered cone sensitivities. The evidence as well as speculations so far suggest that the enhanced perception may not rely on a single mechanism but arise from multiple mechanisms that collaboratively serve to result in the enhancement at different stages. Nevertheless, the complete picture of such mechanisms is not yet clear.

To study the neural representation involved to the extent of higher hierarchical processes, a task involving a complex neural activity, such as attention, was considered; it was presumed that the cognitive process that activates attention would reflect the compensated perceptual experience of color vision variants and would highlight its differences from that of common trichromats. Accordingly, in this study, we investigated differences in neural representation during the observation of the saliency of different colors, which is expected to arouse different attentional levels during the detection task. Chromatically, the same stimuli were used for all color vision types in order to focus on diverse neural processing under the same chromatic conditions, as is the case in the real-life environment, wherein no color adjustments are made purposefully in consideration of sensitivity differences. To the best of our knowledge, this is the first study to investigate the neural response reflecting attention toward the same-color stimuli among various color vision types.

Electroencephalography (EEG) was used to obtain recordings during the visual oddball task, and participants were asked to detect two rarely presented target colors with different saliencies (deviant stimuli) from a sequence of frequently presented, non-target color stimuli (standard stimuli). The purpose of the experiment was to investigate the neural processing of colors with saliency differences in relation to the diversity in color vision and to analyze

the corresponding differences reflected in attention during the detection task among the different color vision types. The front-partial P3 component of event-related brain potentials (ERPs), which is known to reflect allocated attentional resources [19–21], was analyzed as a primary indicator of attention-related neural activity during the time-course of stimulus processing. ERPs are transient neural activities elicited by exposure to external and internal events, providing a broad range of information about sensory and cognitive processing over time [22, 23]. ERP components, such as P3, are identified as a series of observed major peaks and troughs among the minor voltage fluctuations within an analyzed time window. They are identified based on the temporal and spatial domains, with consideration of task conditions and related sensory modality. P3 is one of the most studied ERP components and is known to be evoked by rarely presented task-relevant stimuli and to increase in amplitude with increase in task difficulty [24, 25] reflecting an increase in the volume of spared attentional resources [26, 27]. Due to the lack of study in relation to color saliency and attention-related neural responses especially with color vision variant people, ERP components were also analyzed in exploratory manner. The oddball task is an experimental paradigm that requires participants to engage in the rapid detection of rarely presented task-relevant stimuli, often along with covert or overt responses.

In this experimental paradigm, we asked participants to detect deviant stimuli with overt responses by pressing a button. The same set of stimuli colors was used for all participants to analyze differences in neural activity in the detection of identical colors. We also selected the stimulus chromaticities so that predicted saliencies of deviant stimuli were reversed between color vision types—the deviant stimulus that was more salient for common trichromats was designed to be less salient for anomalous trichromats and vice versa for the other deviant stimulus. P3 amplitude was expected to be increased in response to the less salient deviant compared to the more salient deviant due to an increase in demand for cognitive resource allocation. Thus, a reversed P3 response between deviants, as well as between color vision types, was expected. In addition, we focused on whether there is any neural compensation for stimuli that are considered less salient in anomalous trichromats, as predicted by previous theoretical studies [15].

While the mechanism underlying compensated chromatic sensitivity may be highly complex, our primary focus in this study centers on understanding the differences in the temporal dynamics of attention-related neural activity during the observation of chromatically identical stimuli that differ in saliency and compare them in terms of stimuli saliency and color vision types. This study aims to contribute to the enrichment of knowledge regarding neural activity of color vision variants in relation to higher cognitive process in color perception.

2. Material and Method

2.1. Participants

Nineteen male participants with normal or corrected-to-normal visual acuity participated in this study. Most of them were undergraduate and graduate students at Kyushu University, School of Design (mean age ± standard deviation [*SD*]: 23.32 ± 2.68 years). The participation was restricted to males, given that approximately 10 % of females carry a mutated gene which modifies cone sensitivity, potentially interfere with the performance in our experiment. To identify the color vision type of each participant, the following color vision tests were conducted: Ishihara pseudoisochromatic plate test, Color Assessment and Diagnosis (CAD) test [28], HMC-Anomaloscope (Oculus), and the Farsworth–Munsell 100 hue test. Based on the results, five participants were identified as deuteranomalous trichromats, one participant was identified as a deuteranope, and the others were identified as common trichromats.

Each participant was provided with financial compensation for participation in the experiment. The experimental procedure was approved by the ethics committee of the Graduate School of Design, Kyushu University (Approval No. 316) and was confirmed to be in compliance with the Declaration of Helsinki. Written consent was obtained from each participant prior to the experiment.

In order to be mindful of the perceptual variability in color vision of each individual,

Participant code	Red-green threshold	Color vision type
Participant 14	21.63	Deuteranomalous trichromacy
Participant 07	19.36	Deuteranopia
Participant 02	19.35	Deuteranomalous trichromacy
Participant 18	13.34	Deuteranomalous trichromacy
Participant 03	9.07	Deuteranomalous trichromacy
Participant 16	2.19	Deuteranomalous trichromacy

Table 1. Red-green thresholds and identified color vision types of the participants designated as color vision variant types. In the CAD test, the threshold of 1 represents the average discrimination threshold of common trichromats.

red-green color axis sensitivities were measured using the CAD test. Table 1 shows the results of the measured red-green thresholds of the deuteranomalous trichromat and deuteranope participants. The red-green threshold represents an individual's red-green sensitivity as a deviation from that of common trichromats when their average is considered as 1 [6]. The thresholds based on the CAD test represent the amount of saturation required to perceive the color from the neutral white point along the evaluating color axis in the CIE 1931 color space, which the CAD test uses to select test stimuli colors.

2.2. Apparatus

Stimuli were presented on an LCD monitor (Display++, Cambridge Research Systems Ltd.) in combination with an image processor (Bits#, Cambridge Research Systems) which presented the stimuli in RGB values at a 14-bit resolution. The experimental program was controlled using MATLAB (MathWorks, Inc.) and the psychtoolbox-3 extension [29–31]. A64-channel digital recorder (actiCHamp Plus, Brain Products GmbH) was used for EEG. The active electrodes were placed on the scalp based on a 10–20 layout system using an electrode cap (actiCap slim, Brain Products GmbH).

The timestamps of stimuli onset and behavioral responses by the participants were registered to the EEG amplifier using a trigger box via a parallel port. Photoelectric sensors (MaP1180PS2A, Nihon Santeku) were attached directly onto the display surface, where a small section was used for sending binary signals by changing the luminance level. The signals from photoelectric sensors were used both to record timestamps of the stimuli onset and to identify stimuli colors presented in each trial. Participants used a button with a wire connection to the trigger box to submit their behavioral responses.

2.3. Stimuli

The set of color stimuli were chosen to convey a different saliency contrast when two of the color stimuli were paired to one common pivotal stimulus. The colors were blue-green, orange-tinted red (hereafter simply referred to as red) and green. Common pivoting color was green and target contrasting colors were blue-green and red and they were designated as standard for pivoting color and deviant 1 and deviant 2 for contrasting target colors. The Stimuli were chosen to invoke different attentional levels during attention demanding oddball task based on estimated color saliency gaps between the pairs. In order to carry out the experiment with same stimuli set across color vision types, the relation of the saliency between the pairs were reversed between color vision types while keeping the coherence of the saliency contrast—for common trichromats, the pair with red would be more salient than the pair with blue-green, and for deuteranomalous trichromats and deuteranopes, the pair with blue-green was expected to be more salient than the pair with red.was expected to be more salient than the pair with red.

Each stimulus coordinate was selected from equidistant circumference from neutral gray of D65 in u', v' Uniform Chromaticity Scale Diagram, as shown in Figure 1. The coordinates of the stimuli were (0.1679,0.4670), (0.2278,0.4696), and (0.1817,0.4936) for blue-green, red, and green, respectively, with each being equidistant from D65 (0.1978,0.4683) at a distance of 0.03. In a uniform color space, perceptual differences of colors are represented as Euclidean distances for common trichromats—the more the distance between two points, the larger the perceptual difference. The Euclidean distances of blue-green and red from green in the space were 0.03 and 0.052, respectively.

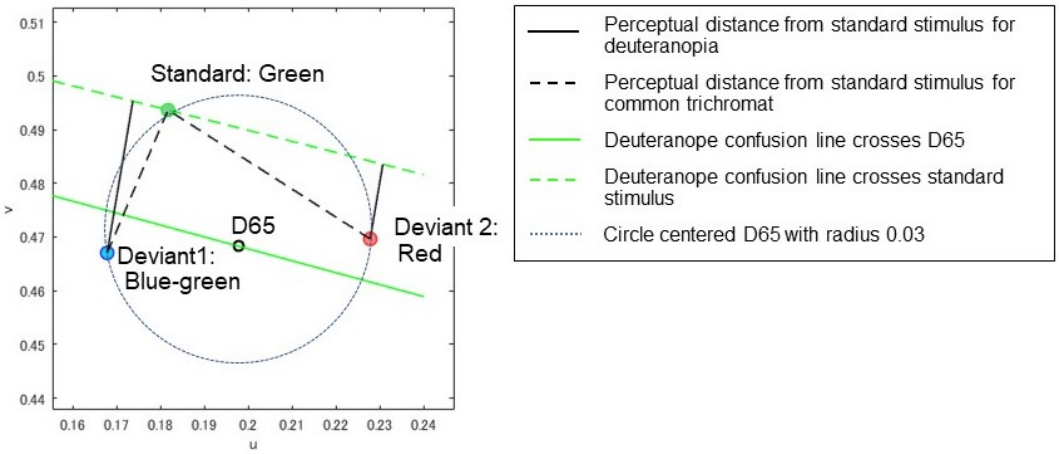

Fig. 1. The coordinates of stimuli in u', v' Uniform Chromaticity Scale Diagram, where perceptual distance is represented in terms of the Euclidean distance for common trichromats. The expected saliency between standard and deviant stimuli is represented by the length of the line for common trichromats (black dotted line) and deuteranope (black solid line).

On the other hand, different interpretation is required for deuteranomalous trichromatic as well as deuteranopic individuals when comprehending perceptual distance in the color space since the uniformity in the space is arranged based on perception of common trichromats. To estimate perceptual distance for deuteranopia as well as its variant deuteranomalous trichromats, confusion lines are needed to be drawn into the color space diagram to represent their reduced dimensionality in the experienced color space. Deuteranopic confusion lines as shown in Figure 1 represent coordinates of colors that look the same to deuteranopia: any colors on any single confusion line present the single perceptual color. In a theory, deuteranopia's color experience is limited to a single color axis of blue–yellow based on the opponent contrast of L and S cone signals. However, several studies have reported that deuteranopes as well as deuteranomalous trichromats exhibit some degree of red-green discrimination as stated in previous section [7–10]. Some studies argue that their color axis does not form a straight line but curved which enables to attain some degree of red-green discrimination. However, color axis of deuteranopia is still a subject of ongoing debate [32]. Nonetheless, in our preliminary experiment where the stimuli were equiluminant and had the same saturation from D65 as this present study, a deuteranope and deuteranomalous trichromats demonstrated identical perception to the colors on the same confusion line. This indicates the close similarity in perceived colors on the same straight edges of a confusion line in this condition. Pridmore reported in his study that perceived color axis of dichromats (all three types; protanopes, deuteranopes, and tritanopes) are found orthogonal to the confusion lines which intersect D65 and D50 in CIELUV based on an assumption that dichromats' color experiences are primarily confined to two opposing colors [33]. Although color axis of deuteranopia is still not entirely clear considering supra-sensitivities reported from afore mentioned studies [7–10], experienced color axis of deuteranopia can be deduced to be near

orthogonal to the confusion line for this stimulus condition. Also, since the stimulus colors used in this study were low in saturation from the neutral gray of D65, we consider the influence of axis curvature would be negligible for this condition. Thus, for a deuteranope and deuteranomalous trichromats in this experiment, we estimated perceptual difference between the two colors as a distance between two points, one from the coordinate of one color and the other was the cross point with the other color's confusion line when two points were connected with orthogonal line as illustrated as solid black line in Figure 1. Although it needs to be emphasized that saliency difference for deuteranopia and deuteranomalous trichromats is still an estimation based on theory as well as empirically acquired behavioral result from preliminary experiment, relative saliency of blue-green and red separately from green were estimated and measured as 0.0263 and 0.0142 respectively.

2.4. Procedure

After the electrode cap were placed on their scalp, each participant was seated in a chair 57 cm from the display surface with eyes fixed at the center of the screen in a dark room. Prior to the oddball experiment, the luminance of the three stimuli colors—blue-green, red, and green—were made equal to 20 cd/m^2 D65, the color used as a background using flicker photometry. Equiluminance measurement was conducted six times for each stimulus. The starting luminance was either 23 cd/m^2 or 17 cd/m^2 and was alternated so that the adjustment direction would alternate between increment and decrement toward 20 cd/m^2 D65 in each measurement. The obtained luminance was averaged and applied to the stimuli luminance later in the oddball experiment. The average stimuli luminance for deviant 1, deviant 2, and standard stimuli was 20.49, 19.74, and 20.11 cd/m^2 for common trichromats, 21.27, 18.96, and 20.60 cd/m^2 for the deuteranomalous trichromat, and 21.43, 19.04, and 20.77 cd/m^2 for deuteranopes, respectively.

The oddball task consisted of frequently presented standard stimuli and rarely presented deviant stimuli. During the presentation sequence, participants were asked to pay attention to randomly appearing deviant stimuli. The task contained one standard (green) and two deviant (blue-green and red) stimuli with the coordinates shown in Figure 1. During the task, participants were asked to pay attention to these two deviants and press a button as soon as they detected them. In each trial, the disk-shaped stimuli were presented in the center of the screen for 400 ms with randomized intervals of 1200–1600 ms. The presented stimulus had a visual angle of 2°, and its edge was diffused with the neutral gray background. The presentation frequency of the standard and deviant stimuli was 8:2, with the ratio of deviants being equal. Ten consecutive trials of stimuli presentation were regarded as one block and repeated 40 times with arbitrary breaks between the blocks. These 40 blocks were then regarded as one session and repeated twice with a 10 min break between the sessions. The task schematic image is shown in Figure 2. In total, 800 trials were conducted (640 standard stimulus trials [green] and 160 deviant 1 [blue-green] and deviant 2 [red] trials). The participants were instructed to refrain from eye blinks during a block to avoid electrooculogram contamination of EEG data. Thus, to maintain the engagement level of participants as well as to alleviate dry eyes, an arbitrary untimed break was provided between blocks. Normally, this between-block rest lasted for less than a minute, with occasional longer breaks and with the period varied among participants. To proceed to the next block, the participants simply pressed down a space key, which prompted the appearance of a fixation cross in the center of the screen to allow better preparation before the initiation of the next block. While one of the fingers was placed on the space key to proceed the task, participants held a rectangular box-shaped device with a button on one end with the other hand. Most participants pressed the button with their right thumb to submit reaction times (RTs) as soon as the detection of deviant stimuli. In each block, the appearance of a deviant stimulus was always preceded by a standard stimulus so that discrimination of the deviants was always in contrast to the standard stimulus. Additionally, only one of the two deviant stimuli, if any, was contained within any single block to avoid confusion among the stimuli.

To avoid any uncertainty about the stimuli instruction with the use of color names, color

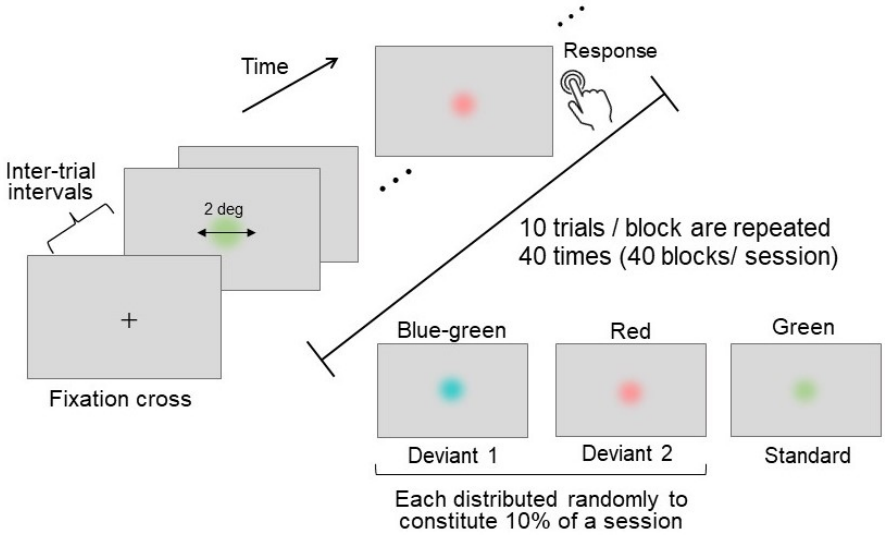

Fig. 2. Schematic representaiton of oddball task, including stimulus types and their corresponding colors. Three distinct colors were used, each assigned either as rarely presented deviant or high-frequent standard stimulus. Each stimulus was presented for a duration of 400 ms, with an inter-trial interval ranging from 1200 - 1600 ms. Participants were asked instructed to press a button immediately upon detection of the deviant stimulus.

names were not used to instruct stimulus type (standard or deviant). Rather than specifying the color names, we let participants recognize deviant and standard stimuli by showing stimulus sequences used in the task. After deviant and standard stimuli were identified by the difference in appearance frequency, three practice blocks were conducted to familiarize the participants with the task procedure.

2.5. EEG recording and data analysis

EEG was recorded and digitized at a sampling rate of 1000 Hz. Recorded EEG was analyzed using EEGLAB [34] installed in MATLAB (MathWorks, Inc.). The data was bandpass filtered between 0.5 Hz to 30 Hz. Further, to enhance data readability and quality, we employed two EEGLAB plugin functions, namely IC Label and Clean raw data. IC Label served to differentiate independent components (ICs) stemming from brain activity versus those originating from non-brain sources. IC identified with over 90 % probability as being related to eye movements, muscle artifacts, or specific channels were subsequently marked for rejection. Additionally, Clean raw data plugin was utilized to identify and eliminate data segments and channels significantly contaminated by noise. We adhered to the rejection criteria recommended by [35] and supplemented this process by interpolating deleted channels with data from neighboring channels, thereby optimizing the data quality before averaged referencing. Finally, as for preprocessing steps, 1000 ms single trial data was extracted from the recorded data and an average pre-stimulus period of 100 ms was removed to establish baseline of the data.

The EEG data was analyzed from two different perspectives: inspection of global activity by analyzing global field power and local potential changes reflected in ERP components. Global field power (GFP) is calculated as standard deviation of evoked potentials derived from simultaneously recorded electrodes at each time points. It serves as quantification of the level of neural activity occurred at each time points across the scalp surface. In contrast, ERP analysis is typically regional focused. ERP components are identified based on criteria such as specific location, time window of appearance, and polarity. The wealth of resources from

the previous studies and established literature, ERPs enables to interpreting and understand the neural activity recorded in the specific region of interest. In order to enhance readability of ERP components and to account for individual differences in anatomical features, we conducted ERP analysis by averaging data from multiple neighboring channels, thereby enabling the analysis on more robust and standardized data. Regional averaged data was obtained from parietal electrodes, including Cz, CPz, and Pz, as well as occipital electrodes including, POz, PO3, POz, PO4, O1, Oz, and O2. These specific electrodes were selected for their consistent waveforms, which improved readability of the ERP waveforms.

As for ERP analysis, P3 component was selected primarily for the target neural indicator for which reflects saliency difference in color; lower the saliency, higher the amplitude reflecting increase in attention. We also analyzed ERPs in an exploratory manner and found P2 also representing activity in relation to saliency difference. These two components were quantified by measuring mean amplitude withing the selected time window, peak amplitude, and peak amplitude latency. Selected time windows were 300 to 600 ms and 190 to 260 ms for P3 and P2 respectively. Both components were analyzed based on the parietal ERPs. The region and time window were chosen based on temporal and spatial prominence of the data and same criterion were used across color vision types.

The differences between deviants in each color vision type were statistically tested using the paired t-test with which p values. Cohen's d was used to measure effect size. In addition, difference between deviant stimuli at each time points were also statistically tested using paired t-test. The same analysis was also caried out on GFP data to compare global activity difference between deviants at each latency.

To analyze spatial characteristics of the ERP components, scalp topographies were computed. Time points of depiction were 150, 225, 400 ms. These time points roughly corresponded with the peak latencies of observed event-related activities based on GFP.

To compare ERPs between different color vision types, differential activity between deviant 1 and deviant 2 were computed. This allowed us to assess and compare the neural responses to distinctive deviants in the time course across color vision types.

2.6. Behavioral data analysis

Mean RTs for each deviant were computed individually for all participants including deuteranopia. Statistical differences between deviants were tested using paired t-test, and effect size was measured using Cohen's d for common trichromats and deuteranomalous trichromats. In the same way, difference between color vision types with each deviant was tested. The repetition of the tests between color vision types was corrected using the Bonferroni–Holm method [36]. Due to sample size limitation, the deuteranope was excluded from statistical comparison between types, but the RTs between deviants were compared using the independent t-test based on multiple trial data of the participant. RTs above 900 ms were identified as outliers and excluded from the analysis.

To examine the performance on the behavioral response, hit rates were computed based on the average of individual rate of responses to deviant 1 and deviant 2. For common trichromats and deuteranomalous trichromats, the hit rates were compared between deviants using paired t-test, and effect size was computed using Cohen's d. The deuteranope was excluded from the statistical comparison. For the non-target standard stimulus, false alarm rates were computed as the mean of individual rates of responses to it.

3. Result

To present the results, the following abbreviations will be used for referring to color vision types: common trichromats as CT, deuteranomalous trichromats as DA. And Deuteranope as D. Additionally, stimulus types will be referred as Dev 1, Dev 2, and Stnd for deviant 1, deviant 2, and standard respectively.

3.1. Behavioral Result

In Figure 3, individual mean RTs are presented in two separate plots; one was for CT and the other was for DA and D color vision type. As for CT, the mean RT for Dev 2 was significantly faster than that for Dev 1 (382 ± 79 [*SD*] ms vs. 393 ± 77 [*SD*], ms; $p_{.adj}$ = 0.002, d = 0.14), whereas there was no significant difference between Dev 1 (414 ± 82 [*SD*] ms) and Dev 2 (418 ± 86 [*SD*] ms) for DA ($p_{.adj}$ = 0.39, d = 0.06). Although the sample size was limited, the participant with D color vision type was associated with a statistically faster RT to Dev2 (374 ± 57 [*SD*] ms) than Dev 1 (393 ± 58 [*SD*] ms), and thus the response to the low saliency deviant was faster (p = 0.041, d = 0.33), contrary to expectation. CT had significantly faster RTs for both deviants than DA (Dev 1: $p < 0.0001$, d = 0.27, Dev2 2: $p < 0.0001$, d = 0.45).

Hit rates, indicating rates of successful responses to deviants, were high in all color vision types. The mean individual hit rates were 99.71% and 99.42% for CT participants, 100% and 99.50% for DA participants, and both 100% for the one deuteranope participant for Dev 1 and Dev 2, respectively. Mean individual false alarm rates, indicating rate of registered responses to non-target standard stimuli, were low in all color vision types (0.1% for CT, 0.05% for DA, and 0.17% for D). False alarm rates provide information about likeliness in detection errors; however, due to lack of registered information, it was not possible to identify which of the deviants was falsely identified as standard.

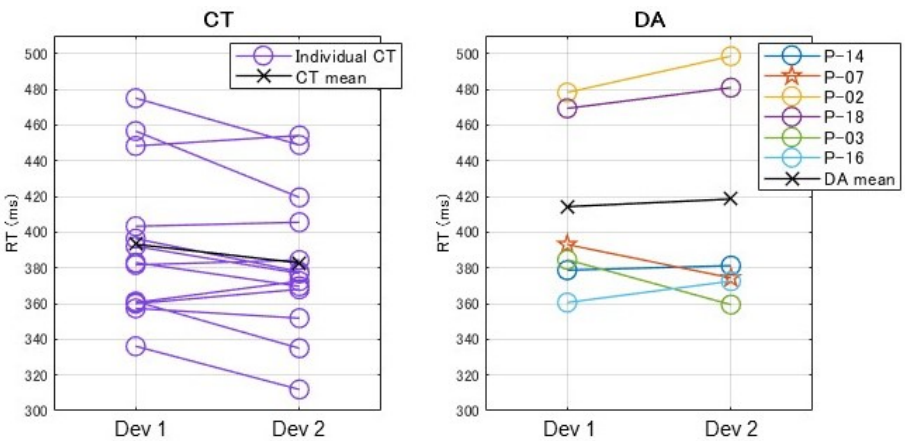

Fig. 3. Indivdual mean RTs for each of the participants, as well as group mean RTs for color vision type CT and DA. For CT participants, mean RTs for Dev 1 and Dev 2 were 393 ± 77 [*SD*] ms and 382 ± 79 [*SD*] ms ($p_{.adj}$ = 0.0009, d = 0.14). For DA participants, the corresponding mean RTs were 414 ± 82 [*SD*] ms and 419 ± 86 [*SD*] ms, with no significant difference ($p_{.adj}$ = 0.39, d = 0.06). Additionally, one participant with color vision type D was grouped with DA participants (Dev 1: 393 ± 58 [*SD*] ms, Dev 2: 374 ± 57 [*SD*] ms). In the legend of DA figure, participants are ordered according to their red-green sensitivity, with those deviating the most from CT appearing at the top of the list. The labeling numbers correspond to the participant codes provided in Table 1

3.2. Electrophysiological Result

The analyses were conducted to highlight both global and regional aspects of the brain activity. Firstly, the global trends were examined based on channel ERPs and GFP analysis, and then analysis on regional activities were conducted based on ERP analysis. The result of the former are presented in Figure 4, and the result of the latter are presented in Figure 5.

3.2.1. GFP and global ERP activity

Figure 4 (A) and (B) presents channel ERP which is a grand-average of each of all 64 electrodes for each deviant, separately for CT and DA, presented with scalp topographies.

The black horizontal lines around 20 to 300 ms indicate the time window where characteristic differences were observed between the color vision types. Within this specific time window, the waveform of DA displayed a sequence of distinct waves characterized by clear peak and troughs. In contrast, the waveform observed in CT during the same time window appears much flatter, with only subtle increase in activities from baseline was observed. This flatness makes it challenging to discern them as distinct waves. This difference is well illustrated by the scalp topographies at the 150 ms and 225 ms time points. While examining the scalp topography, similar trends are found across color vision types, including occipital positivity at 150 ms and frontal positivity at 225 ms. However, With scalp topography images, despite similar trends were observed across color vision types, such as occipital positivity at 150 ms and frontal positivity at 225ms, DA presented larger oscillatory variation between electrodes in response to the deviant stimuli.

In the same context to the oscillatory variation, GFP serves as an informative measure portraying inter-electrode variations capturing the divergence in neural activities between induced by stimulus presentation over time. Notably, as observed in both the channel ERP and scalp topography, GFP values are larger and more pronounced in DA compared to CT, particularly up to around 300 ms. In conjunction with the prominent peak observed around 300 ms mark, the significance of earlier neural activities appears more pronounced in DA than CT. This difference is clearly illustrated in the comparative Figure 4 (E).

Furthermore, as depicted in Figure 4 (C) and (D), time points at which where GFP exhibited statistically significant difference ($p < 0.05$) between deviants are highlighted with thick horizontal blue lines. Notably, within both color vision types, significant differences manifested during the pre-peak periods of the time window associated with the largest peaks. In the case of CT, a faster and more voluminous response was observed for Dev 2, while DA demonstrated voluminous response for Dev 1, with both responses directed toward their respective high saliency deviant stimuli.

3.2.2. ERPs

ERP analysis was primarily performed with parietal P3, as this was our primary neural marker for which saliency difference would be reflected due to the differences in allocated attentional resources. In Figure 5, the left side of the column presents the data recorded from the parietal regions and the right side of the column presents data from the occipital regions. Additionally, the top raw and middle raw present CT and DA data respectively.

As for CT, a significant difference was found in parietal P3 at the parietal region (Figure 5 (A)) at the mean peak amplitude between deviants, with a higher mean amplitude towards Dev 1 ($p = 0.03$, $d = 0.28$, Dev 1: 8.04 uV ± 2.78[*SD*], Dev 2: 7.25 uV ± 2.85 [*SD*]). The mean amplitude also tended to be higher toward with their less saliency deviant, however, there was no significant difference ($p = 0.23$, $d = 0.14$, Dev 1: 5.64 uV ± 2.0 [*SD*], Dev 2: 5.35 uV ± 2.13 [*SD*]).

Unlike CT, DA did not present significant difference in parietal P3 at either at the mean peak amplitude ($p = 0.20$, $d = 0.16$, Dev 1: 5.62 uV ± 2.49 [*SD*], Dev 2: 6.00 ± 2.78 [*SD*]) or the mean amplitude ($p = 0.31$, $d = 0.14$, Dev 1: 3.69 uV ± 1.63, Dev 2: 3.98 uV ± 1.96). As shown in Figure 4, DA have shown characteristic difference from CT during the earlier pre-P3 time window. Thus, parietal P2 which was additionally investigated. As a result, P2 presented significant difference in mean amplitude between deviants ($p = 0.04$, $d = 0.63$, Dev 1: 0.68 ± 0.64 [*SD*], Dev 2: 1.13 uV ± 0.84 [*SD*]), presenting higher amplitude toward their less salient deviant. As with CT, although some participants presented P2, appearance was inconsistent across participants which made it difficult of analyze P2 in CT. Thus, statistical analysis was not performed for CT.

Figure 5 (B) and (D) are ERPs based on recordings from occipital region. Likewise in parietal region, peaks and troughs within the earlier time window preceding the occipital P3 exhibited greater prominence in DA than CT. While the amplitude of these fluctuations are smaller in CT, CT demonstrated more distinct and well-defined waveforms than in their parietal ERPs. Within the period, two prominent components, namely P1 and N2, were

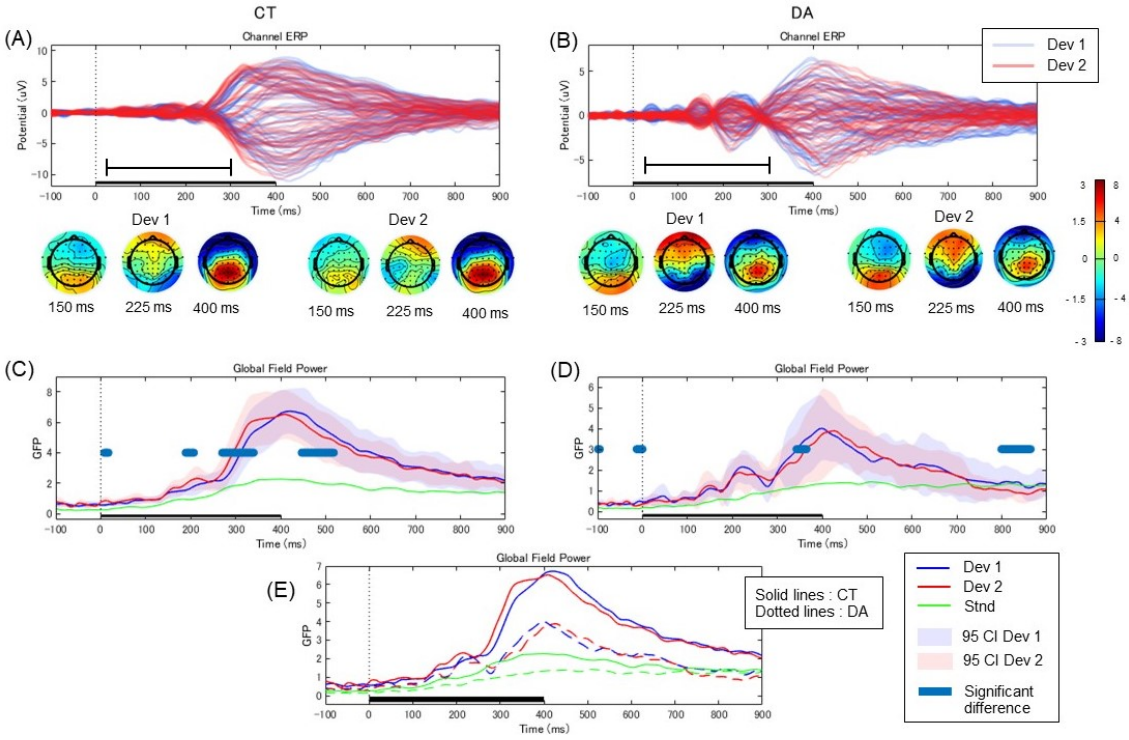

Fig. 4. Channel ERPs with scalp topographies and GFP for CT and DA participants. The different ranges were used between color vision types figure (A) - (D) due to the diferences in amount of activity recorded in the height of their responses around 400 ms. To compare the amount of difference in the activity between color vision type, reffer to figure (E). The figure (E) has identical color coding of the plot as figure (C) and (D)

observed in both color vision types. Brief periods of amplitude differences were found at around P1 and N2 peak latencies exclusively in DA group when tested at each time points (Figure 5 (D)).

Plots presented in Figure 5 (E) and (F) are differential waves of deviants where responses of Dev 2 were subtracted from Dev1. The waveforms are uniquely in alternated relation between CT and DA starting around 150 ms, yet most evident during the time window from 200 – 550 ms. This alterating trends can be observed from both parietal and occipital ERP data, however, parietal region presented clearer shape with consistent amplitude between color vision types

4. Discussion

In this study, our research focused on exploring higher cognitive process, particularly attention, within the temporal domain of neural processing. We aimed to discern how these processes vary between colors differs in saliency when chromatically identical stimuli were used across color vision types. To investigate this, we conducted an attention-demanding oddball task, and subsequently analyzed neural activity from both global and regional perspectives of the recorded data. Our analytical approach included assessment of GFP and channel ERPs for an overview of global neural responses. Furthermore, parietal and occipital ERPs were investigated for neural activities specific to the regions.

The ERP component, parietal P3, was our primary indicator of attention modulation with expectation of increase in amplitude in response to heightened attention allocation during the detection task. As anticipated, CT exhibited higher peak amplitude toward less salient Dev 1, presumably reflecting increased level of attention compared to the more salient Dev 2

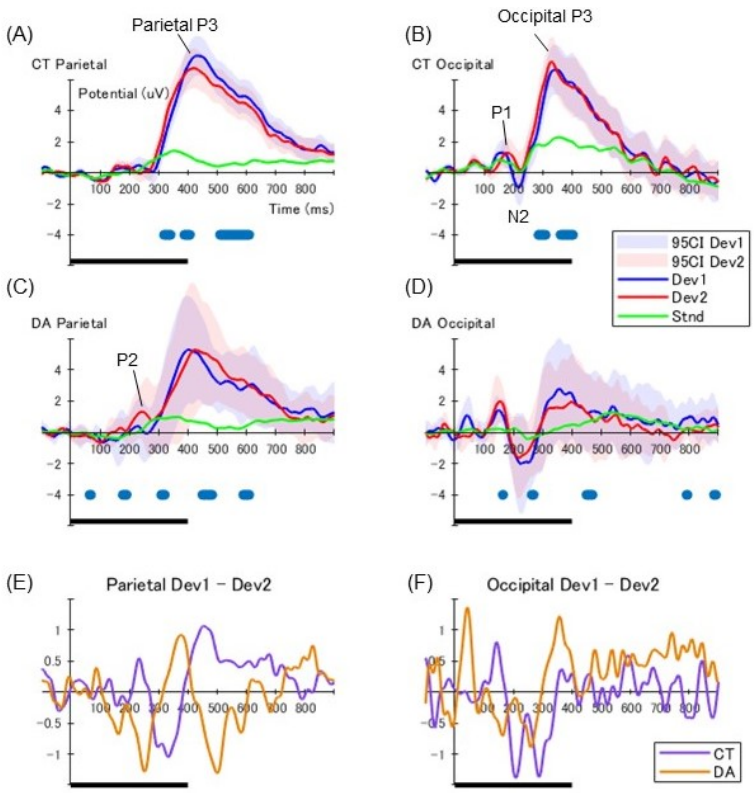

Fig. 5. ERPs plots recorded from parietal and occipital region and differential ERP waveforms between deviants for each color vision types.

(Figure 5 (A)). Furthermore, CT also displayed quicker responses to the more salient Dev 2, as evidenced by a faster RT (Figure 3) as well as faster onset at P3 as illustrated in Figure 4 (A) and (C). All of these results indicate presence of a saliency gap between deviants which relates to distinctive neural process especially during the P3 time window.

Similar to CT participants, DA participants also displayed distinctive neural processes between deviant stimuli. However, unlike the our expectations, these processes occurred within a different time window compared to CT participants. Despite of their diminished chromatic sensitivity, DA participants exhibited heightened neural activity to the less salient Dev 2 during an earlier time window than CT participants, specifically during the P2 component, preceded to parietal P3.

Temporal disparity between color vision types, which underscores the distinct patterns in neural activity between deviant stimuli, particularly emphasizing the increase in amplitude associated with the less salient stimulus, was further elucidated by GFP and channel ERPs, as clearly illustrated in Figure 4. Figure 4 (A) and (B) provide comprehensive depiction of the difference in oscillatory distribution during this earlier time period. Notably, DA exhibited considerably larger amplitude variations than CT at both 150 ms and 225 ms. It is worth noting that the topography observed at 225 ms aligns with the time frame corresponding to the peak latency of P2 component. This observation suggests that frontal activity was particularly pronounced around P2 peak for DA participants.

P2 component also known to be elicited during the attention demanding tasks, often in combination with P3 [37–40]. Series of studies suggests that P2 reflect evaluation process of relevant stimulus features [41–44]. Particularly, P2 with frontal distribution are suggested to indicate top-down oriented approach during the process [45, 46]. Given the contextual information provided, it is plausible to speculate that P2 component observed

in DA participants may reflect an increased intensity in the search for stimulus feature, particularly when chromatically less salient target stimulus was presented.

While relatively limited knowledge exists regarding the distinction in the temporal dynamics of neural processes during the color information processing between common color vision types and variant types of color vision, it is plausible that to making up for reduced chromatic sensitivity, DA participants were required to take extra assessment process before making final judgement on whether to respond to the presented stimulus. This extra step may enabled DA participants to detect target stimuli behaviorally as accurate as CT participants.

With regard to RTs, while CT participants presented faster RTs for the more salient deviant, DA participants RTs did not present difference (Figure 3). Moreover, their individual RTs were inconsistent with their red-green sensitivities. This may indicate the involvement of additional factors in RTs results other than chromatic sensitivity such as difference in response strategy. RTs of both deviants were delayed in DA participants compared to CT participants. This may indicate overall cautious attitude toward behavioral response in DA participants.

For this experiment condition, chromatically identical stimuli were used across participants, irrespective of their color vision types or individual variations in red-green sensitivities (Table 1) in order to directly compare the variation in neural process under uniform stimuli settings. Consequently, saliency differences between deviants were not measured individually. This could be a limitation of this study. However, it is important to note that attempting to equalize the saliency difference between deviants for DA participants would have resulted in significant variations in stimuli colors depending on the participants. Such approach would have deviated from the study's primary aim of maintaining consistent chromatic condition across all participants.

In conclusion, the current study elucidated the distinction in the temporal characteristics on neural process regarding to the detection of saliency different colors among different color vision types. Despite presenting longer behavioral response latencies compared to common trichromats, anomalous participants exhibited notable neural activity in response to saliency difference during an earlier time window. This observed temporal difference may provide valuable insights into the plastic mechanisms that color vision variants employ as a compensatory response to their reduced cone sensitivities.

Future direction of the study will be more in-depth exploration of temporal characteristics of neural process in color vision variants and how top-down mechanism might influences during the process. The direction would further advance our understanding of the neural process which underlies the complemented chromatic sensitivity of color vision variants.

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