Comparative Analysis of Human Color Vision Diversity: Spatiotemporal Dynamics of Attention-Related Neural Activity Toward Color Saliency

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論 文 名：Comparative Analysis of Human Color Vision Diversity: Spatiotemporal Dynamics of Attention-Related Neural Activity Toward Color Saliency
（ヒトの色覚多様性の比較研究：色顕著性に関連する注意の神経活動の時空間ダイナミクス）
区　　分：甲

論 文 内 容 の 要 旨

Color perception is a fundamental aspect of human sensory experience, yet it varies significantly across individuals due to genetic and physiological diversity in the visual system. Most humans are trichromats, perceiving colors through three classes of cone cells with sensitivities that generally align with predictions based on opponent-processing models. However, minority color vision phenotypes often deviate from the predictions, demonstrating enhanced color sensitivity that differs from typical trichromats and suggesting unique processing mechanisms. The precise neural and perceptual mechanisms behind this enhanced sensitivity remain elusive. Given the role of colors as versatile navigation and communication tools, accurately assessing sensory differences and similarities across color vision types is essential to deepening our understanding of the perceptual characteristics and underlying mechanisms for both typical and minority phenotypes.

This dissertation investigates how variations in cone sensitivity influence both neural activity and behavioral performances across different color vision types. Specifically, it examines how neural responses reflect differences in color saliency by analyzing the broad spatiotemporal characteristics of event-related potentials (ERPs) in both typical and anomalous trichromats. Two target stimuli (red and blue-green) were chosen to create different levels of saliency during a discrimination task from a common non-target stimulus (green), allowing comparison of perceived saliency across color vision types. Although the chromatic properties of these stimuli remained constant, their perceived saliency was reversed between the color vision types, enabling direct comparison of neural and behavioral responses. This approach also simulates real-world conditions, where individuals rely on consistent physical light properties to perceive colors without chromatic adjustments.

Using EEG to record ERPs during an attention-demanding oddball task, this study examines how attentional resources are modulated by chromatic stimuli with varied saliency. The analysis includes both categorical distinctions and continuous chromatic sensitivity differences to address individual variability within groups, particularly in anomalous trichromats, where traditional categorical analyses might otherwise mask subtle within-group variations. A linear mixed-effects model was applied to both behavioral and neural data to explore how continuous

variations in chromatic sensitivity shape perceptual and neural responses.

The findings revealed both shared and distinct characteristics of behavioral and neural processing across color vision types. For typical trichromats, both behavioral and neural responses consistently reflected saliency differences, aligning with expectations based on their sensory characteristics. Specifically, reaction times (RTs) were generally faster for the more salient red stimulus, and the spatiotemporal ERP analyses revealed faster, stronger, and more spatially widespread activation for the red stimulus. In contrast, anomalous trichromats did not show a distinct neural response pattern when comparing the two target stimuli. However, when each target was compared to the common non-target green stimulus, anomalous trichromats showed a faster neural response to the more salient blue-green stimulus, confirming the expected saliency difference. Although both color vision types demonstrated faster neural response to their respective more salient target stimuli, the spatiotemporal ERP pattern between groups were not markedly different.

RT analysis indicated that continuous chromatic sensitivity provided a better fit compared to categorical distinction, highlighting nuanced sensory variations reflected in behavioral performance. While the overall RT patterns suggested the influence of reduced chromatic sensitivity of anomalous trichromats, RTs pattern did not support reversal saliency relationship, indicating more complex relationship between chromatic sensitivity and behavioral responses.

These results highlight the robust sensitivity of typical trichromats along the red-green axis, while anomalous trichromats exhibited more nuanced responses to saliency, reflecting complex relationships between their chromatic sensitivities and corresponding behavioral and neural responses. Although both color vision types responded faster to their respective more salient target stimuli, suggesting shared processing mechanisms, anomalous trichromats showed more ambiguity in response to saliency differences. This ambiguity may suggest the presence of enhanced perceptual mechanisms, though the specifics remain unconfirmed. To verify the contribution of such mechanisms, further research with larger sample sizes is necessary to confirm and extend these findings.