

UC Merced

Proceedings of the Annual Meeting of the Cognitive Science Society

Title

Plasticity and Speed-Accuracy Trade-Off in Color Discrimination: Insights from the 100-Hue Test

Permalink

<https://escholarship.org/uc/item/05g309z1>

Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 47(0)

Authors

Qiao, Yanan

Kawabata, Yasuhiro

Publication Date

2025

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Plasticity and Speed-Accuracy Trade-Off in Color Discrimination: Insights from the 100-Hue Test

Yanan Qiao (yanan.qiao.x8@elms.hokudai.ac.jp)

Department of psychology, Graduate School of Humanities and Human Sciences, Hokkaido University
Hokkaido, Japan

Yasuhiro Kawabata (kawabata@let.hokudai.ac.jp)

Department of psychology, Graduate School of Humanities and Human Sciences, Hokkaido University
Hokkaido, Japan

Abstract

This study examines the plasticity of color discrimination and the speed-accuracy trade-off in color discrimination using the 100-hue test. To prevent ceiling effects from task simplicity, an unprecedentedly short time limit of 75 seconds was implemented, a novelty of this study. Unlike conventional 100-hue tests, accuracy rate—rather than total error score—was used to assess color discrimination ability due to its preciseness. The results showed that practice enhances color discrimination accuracy by 40% to 59%, with significant improvements observed after only three trials. Additionally, longer response times correlate with higher color discrimination accuracy. These findings suggest that color vision is highly plastic, with color discrimination ability improving significantly after three practice trials, and that a speed-accuracy trade-off exists in color discrimination.

Keywords: 100-hue test; accuracy; color discrimination; plasticity; speed-accuracy trade-off.

Introduction

Skilled basketball players execute accurate shots through muscle memory of movements developed from repeated skill practice. Similarly, experienced employees can type without looking at the keyboard, relying on muscle memory of key positions on the keyboard, while seasoned drivers make faster decisions based on road conditions compared to novices. These phenomena result from perceptual learning, which refers to a long-term enhancement of perceptual ability through experience (Sasaki, Nanez & Watanabe, 2010). This process induces changes in the sensory and perceptual systems, occurring at behavioral and physiological levels and reflecting brain plasticity (Kawato et al., 2014). Neuroplasticity is the brain's ability to reorganize its structure and function in response to environmental or physiological changes (Akkoyunlu, 2020) and can be categorized into injury-induced and training- and learning-induced plasticity. Injury-induced plasticity involves cortical reorganization induced by the central nervous system or peripheral nerves to compensate for lost functions after injury. Training-induced plasticity, also known as use-dependent plasticity, occurs alongside the acquisition of perception and motor skills (Dinse & Merzenich, 2002). Expanding literature on perceptual learning can clarify the brain's perceptual and plasticity mechanisms and provide a scientific

foundation for improving and restoring impaired perceptual functions.

Research on training- and learning-induced plasticity spans multiple sensory domains. Regarding auditory perception, training leads to long-term modifications in auditory cortical function and brainstem frequency-following responses (Irvine, 2018). Regarding olfaction, experience-dependent plasticity enhances odor detection and helps accurately and quickly discriminate odors (Abraham et al., 2014). Regarding the somatosensory system, proprioceptive function in patients with mild to moderate Parkinson's disease can improve through somatosensory-focused motor training (Elangovan, Tuite & Konczak, 2018). Regarding vision, rewards can induce visual perceptual learning through reinforcement processes (Wang et al., 2019). At the earliest stages of visual cortical processing, functional properties of neurons exhibit high plastic, integrating information from an extended visual space range than previously assumed (Gilbert, 1998). Visual performance in vernier acuity and stereo depth perception improves rapidly, with significant learning effects observed in under an hour of training (Fahle, Edelman & Poggio, 1995). Regarding brightness contrast-based complex grating discrimination tasks, performance steadily increases with practice, reaching 95-100% accuracy within 50-60 trials (Fiorentini & Berardi, 2002, p.170). While extensive research has explored training and learning-induced plasticity across sensory modalities, including hearing, olfaction, somatosensory system, and vision, visual plasticity studies have predominantly focused on factors influencing plasticity, neuronal adaptation, higher-order perception, and brightness discrimination. However, literature addressing plasticity in color vision remains limited. Color plays a crucial role in human perception, conveying essential information about the physical environment (Shevell & Kingdom, 2008). For example, traffic light colors indicate whether it is safe to cross the road, while fruit color signals ripeness. Given the significance of color discrimination ability, it is essential to expand its research. Regarding the plasticity of color discrimination, Kawabata and Kawabata (2014) conducted 11 repeated color discrimination experiments using the 100-hue test with an extended time limit. Results showed a progressive decline in error scores (gradually 0) across trials, demonstrating the effects of perceptual learning. However, two limitations can

be identified in this study. First, the extended time limit may have been insufficient to reflect individual differences in color discrimination ability (Kawabata et al., 2020). The simplicity of the experimental conditions also introduced interpretational constraints, leading to a ceiling effect. Second, the study relied on total error scores to explain the decline in color discrimination ability, a common approach across literature in the 100-hue test use for color discrimination ability. Total error score represents the sum of all error scores, whereas accuracy rate reflects the proportion of correct identifications. For example, two participants (A and B) with identical total error scores of 100 but differing accuracy rates (e.g., 0.5 and 0.8) exhibit distinct performance patterns. A made fewer correct identification and had a lower average error score for each color block, indicating dispersed errors that are not concentrated on specific color blocks. Conversely, B made more correct identifications and had a higher average error score for each color block, indicating concentrated errors on a few color blocks, with severe errors on more challenging color blocks. Despite the same total error score, their performance patterns and error distribution patterns significantly differed during tasks. A made fewer correct identifications, indicating lower discrimination ability, while B made more correct identifications, indicating higher discrimination ability. This distinction suggests that accuracy rate better represents color discrimination ability than total error score.

Therefore, this study employed a modified 100-hue test with a shortened time limit and used accuracy rate instead of total error score to examine the plasticity of color discrimination and the effects of perceptual learning. In addition to exploring plasticity and learning effects under time constraints, this study also investigated decision-making processes, an essential area of psychological research. Time pressure is crucial in many decision-making contexts, with a well-documented effect being the speed-accuracy trade-off (Katsimpokis, Hawkins & van Maanen, 2020), where individuals either prioritize speed at the expense of accuracy or slow down to enhance precision. A previous study on the speed-accuracy trade-off in color discrimination examined red-green discrimination under eight-time constraints (150–800 milliseconds) (Yellott, 1971). Results indicated that response accuracy ranged from 0.74 to 0.99, indicating that the longer the time limit, the higher the discrimination accuracy. However, this study was limited to two specific colors (red and green) and did not encompass the entire hue spectrum. The findings, therefore, lacked generalizability, as they did not account for variations in brightness, saturation, and hue. Expanding speed-accuracy trade-off research to a broader hue range can enable a more comprehensive assessment of color perception and verify and expand the cognitive decision-making model.

In summary, this study had two primary objectives: a) to investigate the plasticity of color discrimination ability and the effects of perceptual learning, and b) to examine the speed-accuracy trade-off across the entire hue spectrum. Two hypotheses (H) were proposed. First, the color discrimination

ability will significantly improve with practice (H1). Second, a speed-accuracy trade-off would be observed in color discrimination across the full hue range (H2).

This is the first study to investigate the accuracy and plasticity of color discrimination using different shortened time limit conditions.

Method

Participants Recruitment

Sixteen college students from Hokkaido University (11 females and 5 males) aged 19 to 34 years [mean (M) = 22.440, standard deviation (SD) = 3.320] participated in this experiment. Participants were recruited from psychology courses and lectures and received bonus points for participation.

This study was reviewed and approved by the Ethics Committee of Hokkaido University and conducted in accordance with the ethical standards of the Declaration of Helsinki (1996). Informed consent was obtained from all participants.

Stimuli and the Apparatus

This study used the 100-hue test (ND-100) from Nippon Color Enterprise Co., Ltd., which was inspired by the Farnsworth-Munsell 100-hue test. While the two tests differ slightly in color composition and number, the 100-hue test provides more specific results due to its extensive range of color patches (Rigby et al., 1991). Additionally, it has proven more accurate than similar assessments (Yang et al., 2005) and can be completed efficiently (Lakowski, 1969).

The equipment used for the 100-hue test is shown in Figure 1. It comprises 100 color caps, arranged together to form a hue ring based on the Munsell color system, encompassing the primary five hues (red, yellow, green, blue, and purple) and their intermediate hues (orange, yellowish-green, bluish-green, bluish-purple, and reddish-purple). Color vision was assessed by requiring participants to rearrange the colored bottle caps. All bottle caps used in the test have a Munsell value of 6, following the internationally recognized Munsell color system, which numerically represents hue, value, and chroma.

The light source was a dimmable D65 lamp. Table 1 presents the illumination levels used in the experiments. The CIE x, y values in the table represent coordinates in the CIE 1931 color space, where the Yxy (Y : brightness) coordinates predict the perception of unique hues. Some variations in

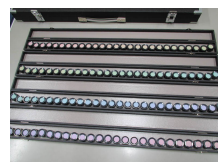


Figure 1: Experimental Apparatus.

Table 1: Experimental illumination.

Experimental Conditions	Illuminance (Lux)	Maximum (Lux)	Minimum (Lux)	CIE	
				x	y
105-second	714.545 (±560.278)	1840	89.600	0.3225 (±0.0123)	0.3407 (±0.0162)
90-second	755.455 (±587.495)	1920	64.700	0.3158 (±0.0187)	0.3330 (±0.0202)
75-second	774.864 (±640.641)	2320	71.800	0.3181 (±0.0172)	0.3349 (±0.0188)

illumination was observed between experimental conditions. However, Knoblauch et al. (1987) found that illumination levels above 5.7 lux do not affect color discrimination in young participants. The lowest illumination level in this study was 64.700 lux, ensuring that lighting conditions did not influence color discrimination performance.

Procedure

Participants entered the experimental room in groups of four and were seated at a table with the experimenter. The experiment commenced 15 minutes after entry to allow participants to adapt to the experimental lighting conditions. During this period, the experimenter explained the study’s purpose and provided instructions on operating the equipment.

The test comprises four boxes, each containing 27 colored caps as stimuli, with two fixed reference caps at either end. The remaining 25 caps were freely movable within a designated time limit. Participants first randomized the order of the 25 movable colored bottle caps. During the experiment, they rearranged the caps using the fixed caps at both ends as reference points, ensuring a gradual and smooth color transition. When correctly arranged, the hues formed a continuous gradient. Each cap was marked on the back with a number corresponding to its original position, allowing the calculation of the error score (ES)—the degree of mismatch between each adjacent caps (Kawabata et al., 2020). As previously mentioned, accuracy is a more precise indicator of color discrimination ability than the error score. Therefore, this study measured accuracy as the proportion of correctly placed caps (ES = 0) out of 100.

For participants with normal trichromatic vision working in color-related industries, the recommended time limit per box in the 100-color test is two minutes. However, in previous studies, the 120-second condition was too simple due to the extended time limit, resulting in a ceiling effect that limited data interpretation. To address this, the present study shortened the time limits and increased task difficulty to examine color discrimination plasticity under more demanding conditions. Another objective was to verify the speed-accuracy trade-off in color discrimination across the entire hue wheel, necessitating multiple time constraints.

Based on the two-minute standard, 15, 30, and 45 s were shortened, and 105, 90, and 75 s were set, respectively. The 75-second condition, not previously tested, was added to assess how significantly reduced discrimination time affects performance and plasticity. The experiment consisted of three rounds, each following the order 105, 90, and 75 s. This sequence was repeated three times for each experiment,

totaling nine experiments. The order of the nine experiments was 105, 90, 75, 105, 90, 75, 105, 90, 75, 105, 90, and 75 s. The average interval between each experiment was 47.670 (±18.180) days.

Results

Accuracy

The within-subject analysis of the two-way variance (ANOVA; experimental condition, rounds) revealed a significant main effect of the number of experimental repetitions ($F(2,30) = 26.027, p < .0001$), indicating that color discrimination accuracy improved significantly with continued practice. Multiple comparisons showed significant differences in accuracy between the first and second experiments ($p = .0390$), the first and third experiments ($p < .0001$), and the second and third experiments ($p < .0001$). These results suggest that accuracy increased significantly from the second experiment, reflecting the effect of perceptual learning. Figure 2 illustrates changes in accuracy across different experimental conditions and rounds. The horizontal axis represents the experiment number, with the three experiments conducted in the first, fourth, and seventh trials; the three 90-second condition experiments conducted in the second, fifth, and eighth trials; and the 75-second condition experiments conducted in the third, sixth, and ninth trials. The vertical axis represents accuracy, with the green line representing the 105-second condition, the orange line representing the 90-second condition, and the red line representing the 75-second condition. The figure shows that accuracy increased across all three experimental conditions and support H1 that color discrimination ability improves with practice. The average accuracy rates for the three 105-second condition experiments were 0.512 ± 0.225 , 0.669 ± 0.219 , and 0.721 ± 0.225 . For the 90-second condition, the averages were 0.454 ± 0.173 , 0.628 ± 0.227 , and 0.680 ± 0.246 , and for the 75-second condition, they were 0.369 ± 0.201 , 0.507 ± 0.226 , and 0.587 ± 0.220 .

The rate of increase in average accuracy rate, representing the percentage improvement in accuracy across the three experiments within each condition, was also calculated. Figure 3 depicts these changes, with the horizontal axis representing different experimental rounds and the vertical axis representing the rate of increase. The green, orange, and

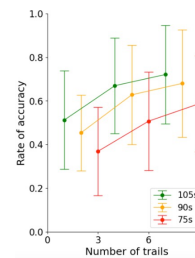


Figure 2: Changes in the Rate of Accuracy.

red lines correspond to the 105-second, 90-second, and 75-second conditions, respectively. The figure shows that across all conditions, the rate of increase was higher between the first and second experiments but lower between the second and third experiments, and accuracy rate increased in three experiments, which verified H1 from another perspective.

In the 105-second condition, the increase in accuracy between the first and second experiments is 30.660%, while the increase between the second and third experiments was 7.770%. For the 90-second condition, these were 38.300% and 8.400%, respectively, and for the 75-second condition, they were 37.490% and 15.780%, respectively. The overall rate of decrease between the first and third experiments was 40.800%, 49.860%, and 59.190% in the three conditions, respectively.

Regression analysis of the average accuracy rate for each condition showed that curve regression provided a better fit than linear regression. The regression curve is presented in Figure 4, where the horizontal axis represents the number of experiments, and the vertical axis represents the accuracy rate. The green, orange, and red lines correspond to the fitting results of the 105-second, 90-second, and 75-second conditions. The regression equations for accuracy rate are as follows (x represents frequency): $y = 0.44 + 0.08x - 5.9E-3x^2$ for the 105-second condition, $y = 0.27 + 0.11x - 6.74E-3x^2$ for the 90-second condition, and $y = 0.17 + 0.08x - 3.23E-3x^2$ for the 75-second condition. The coefficient of determination (R2) for all three conditions is 1.0, indicating a perfect fit. As shown in the figure, the regression curve exhibits a downward trend after three experiments under the 105-second and 90-second conditions, while the regression curve of the 75-second condition follows an upward trend which means that after three practice sessions, accuracy under 105-second and 90-second conditions will decrease, while accuracy under 75-second condition will continue to increase. As for three practice sessions, figure 4 shows that accuracy is increasing regardless of the condition, which once again verifies H1.

Speed-Accuracy Trade-off

The results of the two-way (experimental condition, rounds) ANOVA within-subject analysis revealed a significant main effect of the experimental condition ($F(2,30) = 23.987, p < .0001$), indicating that accuracy rates varied across conditions, indicating the presence of a speed-accuracy trade-off. Multiple comparisons showed significant differences

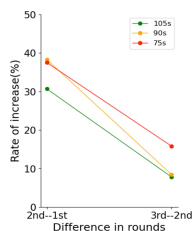


Figure 3: Increase Rate of Average Accuracy.

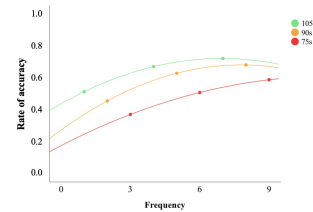


Figure 4: Curve Fitting of the Rate of Accuracy.

between the 105-second condition and the 90-second condition ($p < .0001$) and between the 105-second condition and the 75-second condition ($p < .0001$). These findings indicate longer time limits resulted in higher accuracy, whereas shorter time limits led to lower accuracy. The interaction between the experimental conditions and experimental rounds was not significant ($F(4,60) = 0.194, p = .9410$), suggesting that these two factors independently influenced color discrimination ability.

As shown in Figure 2, the 105-second condition consistently produced the highest accuracy. Regarding accuracy progression, performance under the 105-second condition remained higher than that under the 90-second and 75-second conditions. Results in Figure 2 support H2, that a speed-accuracy trade-off would be observed in color discrimination across the full hue range. Regarding the average accuracy rates across the three experiments, the 105-second condition was 0.634 ± 0.240 , the 90-second condition was 0.587 ± 0.238 , and the 75-second condition was 0.490 ± 0.234 . These results once again confirm that the 105-second condition produced the highest overall accuracy.

Figure 5 (a), Figure 5 (b) and Figure 5 (c) illustrate the accuracy rate changes for all 16 participants under the 105-second, the 90-second, and the 75-second conditions, respectively. Since summarizing the results of all participants in a single graph would result in the overlapping data and obscure individual trends, participants were divided by gender, and their results were presented in the two separate graphs. The red line on the left represents the 11 female

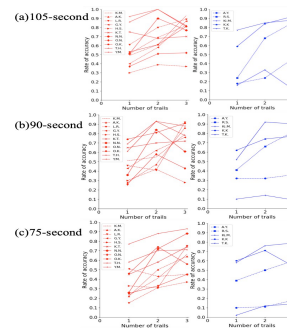


Figure 5: Changes in accuracy of 16 participants under three conditions (the upper (a) represents results of 105-second, the middle (b) represents results of 90-second, and the lower (c) represents results of 75-second).

participants, while the blue line on the right represents the five male participants. The horizontal axis represents the number of experiments, while the vertical axis represents the accuracy rate. The graphs indicate that individual trends in accuracy rate changes vary considerably, reflecting significant individual difference in color discrimination ability. Ignoring individual differences, by focusing on the figure, I found that for most participants, accuracy rate in the third experiment was higher than that in the first experiment, indicating that color discrimination ability has been improved overall, which is consistent with H1. And all the participants achieved higher discrimination accuracy under the 105-second condition, further supporting the superior color discrimination performance observed under this condition which once again confirmed H2.

Effects on Perceptual Learning

Serial Dependency Ordinary least squares regression was used to assess whether trial-related accuracy was influenced by the stimulus type of the previous trial. The model evidenced a moderate fit (adjusted $R^2 = 0.408$) but was not significant ($F(4, 1) = 2.722, p = .1320$). No predictors were significant, including prior accuracy ($\beta = 0.222, p = .6170$). The Durbin-Watson statistic (2.207) revealed no autocorrelation; thus, no significant sequential dependency was indicated in accuracy across trials.

Color Naming Bias A post experiment questionnaire was administered to examine the effects of color naming on discrimination performance. Fifteen of the 16 participants responded, and the participants were designated based on their self-reports into two groups: naming ($n = 2$) and non-naming ($n = 13$). No significant difference was found through the one-way ANOVA performed to compare the accuracy of the two groups ($F(1, 133) = 3.850, p = .0520$). This outcome implies that consciously naming colors during the task did not significantly influence the accuracy of hue discrimination.

Discussion

This study tested two hypotheses. First, it was hypothesized that color discrimination ability would significantly improve following repeated practice. The results supported this hypothesis, showing that across all nine experimental conditions, accuracy declined significantly by the second round, reflecting perceptual learning effects. In the 105 s, 90 s, and 75 s conditions, overall accuracy increased by 40.800%, 49.860%, and 59.190%, respectively, highlighting the high plasticity of color vision and aligning with Lunghi, Burr, and Morrone (2013).

Further analysis illuminated the relationships between short-term training effects, long-term plasticity, and critical period mechanisms. The participants did not receive explicit color-related training beyond the experimental sessions. However, they exhibited considerable advancement in their color identification accuracy over 367 days, which indicated the long-term plasticity of color-processing regions of the brain. This finding is congruent with the findings reported by

Hamilton and Mathalon (2023), who demonstrated that experience-driven plasticity could occur without targeted intervention. Perhaps persistent and repeated stimulation or months or even a lifetime (Martin, Grimwood & Morris, 2000) can cause the long-term potentiation mechanism to strengthen synaptic connections (Levenson et al., 2002; Teyler & DiScenna, 1987). Conversely, short-term training effects are typically transient even though they can induce rapid cognitive improvements (Horiuchi & Nagai, 2024): their effects last merely between milliseconds and several hours (Citri & Malenka, 2008; Kurzwski et al., 2022). The brain exhibits heightened plasticity during a critical period during early development, enabling rapid neural reorganization in response to environmental input (Levelt & Hübener, 2012). Plasticity persists even after this window shuts but depends increasingly on training intensity and duration (Fournier & Teskey, 2014; Jung & Xie, 2016). Thus, the current findings align with mechanisms researchers have established as underpinning long-term plasticity.

Developmentally, newborns are minimally color-sensitive (Dobkins, 2009). Trichromatic color vision begins at around two to three months (Teller, 1998). However, visual evoked potentials appear for red-green stimuli at four weeks and are observed for blue-yellow between six and eight weeks (Crognale, 2002b). Infant cone photoreceptors are immature: they are less elongated and more sparsely packed (Yuodelis & Hendrickson, 1986), which limits their ability to discriminate low-saturation colors despite trichromacy (Knoblauch, Vital-Durand & Barbur, 2001). Color vision sensitivity improves by the time an infant is six months old, enabling better color recognition in varied conditions (Dannemiller, 1988). Color vision approaches adult levels between six and ten years, even though minor deficits remain in tasks such as distinguishing subtle differences (Widen, Russell & Broesch, 2010). Neural responses attain adult levels between 12 and 14 years (Morrone, Burr & Fiorentini, 1990), and color vision matures completely between 17 and 18 years (Crognale, 2002a). Lunghi, Burr, and Morrone's (2013) finding that P-cells retain plasticity beyond the critical period further supports the current study's results, as accuracy improved significantly with practice, reaching 0.721, 0.68, and 0.587 across the three conditions. However, these results differ from those of Kawabata and Kawabata (2014), who reported that after 11 practice sessions, the total error score approached zero, suggesting near-perfect color discrimination accuracy. Two key differences may explain this discrepancy. First, Kawabata and Kawabata's (2014) 120-second time limit allowed participants ample opportunity to sort and refine their choices, leading to higher accuracy. In contrast, the shorter time limits in this study required faster performance, limiting opportunities for correction and refinement. Second, whereas Kawabata and Kawabata (2014) conducted 11 trials under a single condition, the present study implemented only three trials per condition across nine conditions, providing fewer opportunities for participants to achieve maximal performance.

The rate of increase in accuracy was higher in the difficult 75-second condition than in the easier 105-second condition. Two factors likely contributed to this result. First, the sequential progression of experiments from easy to difficult influenced the 75-second condition, benefiting from improvements in the previous two conditions. Hochstein and Ahissar (2002) demonstrated that training under a simple condition leads to immediate improvements in more difficult conditions, whereas training exclusively under difficult conditions does not necessarily yield improvements, even with extensive practice. Similarly, Sutherland and Mackintosh (1971, as cited in Ahissar & Hochstein, 1995) found that animals trained in simple discrimination performed more accurately on complex tasks than those trained only on difficult problems from the start. This suggests that under easier conditions facilitates learning and performance in more challenging tasks. The 105-second and 90-second conditions, being relatively simple, likely contributed to greater accuracy under 75-second condition. As practice continued, 75-second condition was increasingly influenced by the improvements in the previous two conditions, so the discrimination will become more accurate, leading to higher accuracy. Second, 75-second condition was inherently more difficult, leaving more room for improvement. In the first experiment, accuracy under 105-second condition exceeded 0.500, and after three trials, it surpassed 0.700. By contrast, 75-second condition began with an accuracy of 0.370, improving to 0.587 after training. The smaller margin for improvement in the 105-second limited accuracy gains, whereas the low initial accuracy in the 75-second condition left substantial room for improvement, resulting in a greater rate of increase. The second hypothesis, predicting a speed-accuracy trade-off in color discrimination across the full hue spectrum, was supported by the experimental results. Accuracy was highest under 105-second condition, lower under 90-second condition, and lowest under 75-second condition, indicating that longer discrimination times yielded higher accuracy. These findings align with the results of Blurton, Feifel, and Gondan (2023), which showed that responses with shorter time constraints tend to be faster but less accurate compared to those with longer time constraints, confirming the presence of a speed-accuracy trade-off. This trade-off can be explained by the diffusion model (Ratcliff & McKoon, 2008). According to this model, observers continuously sample evidence from a stimulus (or its memory trace) until the accumulated evidence reaches a decision boundary (Wang, 2021). In a speed-accuracy trade-off, reducing boundary separation allows participants to respond faster but with lower accuracy. Conversely, increasing boundary separation will produce slower and more accurate responses. Because the amount of evidence required is small, the accuracy of the decision is relatively low. Conversely, by increasing boundary separation and making boundary farther away, participants need to accumulate more evidence to decide. Decision-making time is relatively long, resulting in higher accuracy due to greater evidence accumulation.

These findings support perceptual learning theories and suggest that color perception is highly plastic and trainable. The rapid improvement noted through practice indicates dynamic processing and enriches the extant cognitive models. The speed-accuracy trade-off corroborates decision-making theories, and the improved performance observed through training suggests the involvement of both low-level visual and higher-order cognitive processes. In sum, these results enhance the existing understanding of how perceptual and cognitive systems interact in color vision.

These findings have two main applications. First, they support improvements in professional training and medical rehabilitation. Given the high plasticity of color vision, systematic training can enhance color discrimination in fields like pathology, aviation, and design, boosting work efficiency. They also suggest developing specialized color training tools for individuals with vision impairments to aid rehabilitation and partially restore function. Second, the findings inform AI optimization. Since color discrimination can improve with training, AI systems can be designed to better match human color vision, enhancing adaptability and performance in color-based tasks.

This study has two limitations. First, it involved only young adults, limiting generalizability; future research should include older adults to examine age-related differences in color vision plasticity. Second, each condition was practiced only three times; more trials are needed to assess continued improvement.

Recent findings suggest that the sequence dependence can prejudice perceptual judgments, particularly in conditions of weak stimulation (Cicchini, Mikellidou, & Burr, 2024). The present study randomized the box order and employed a 3-minute inter-stimulus interval (Lidström, 2023) to effectively mitigate this bias. Regression analyses indicated minimal sequential effects by confirming that the previous box type and accuracy did not significantly influence current performance. In terms of the color naming bias, no significant difference in the discrimination accuracy was found between participants who reported naming colors and those who did not. This outcome corresponds with the extant evidence that perceptual rather than linguistic mechanisms govern color discrimination when verbal labeling is not explicitly required (Roberson & Hanley, 2010; Thierry et al., 2009). Taken together, these findings endorse the conclusion that the learning effects observed in the present study primarily reflect changes in the perceptual processing, which are essentially independent of sequence dependence or language-mediated strategies.

Based on these findings, three conclusions can be drawn. First, color vision is highly malleable, with accuracy improvements of 40% to 59% after practice. Second, since accuracy in the second round was higher than in the first, color discrimination ability improves significantly after just three practice sessions. Third, longer reaction time correspond to higher color discrimination accuracy, confirming the existence of speed-accuracy trade-off in color discrimination.

Acknowledgments

This research was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (Grant Number: 23K28171). This study was conducted at the Graduate School of Humanities and Human Sciences, Hokkaido University. The authors thank Prof. Yasuhiro Kawabata for allowing participant recruitment from his course. The authors also express gratitude to all participants for their time and cooperation.

References

- Abraham, N. M., Vincis, R., Lagier, S., Rodriguez, I., & Carleton, A. (2014). Long term functional plasticity of sensory inputs mediated by olfactory learning. *eLife*, 3, Article e03721.
- Ahissar, M., & Hochstein, S. (1995). The role of attention in learning simple visual tasks. In M. Fahle & T. Poggio (Eds.), *Perceptual learning*. The MIT Press.
- Akoyunlu, B. (2020). *Functional changes in the human cortex over the course of visual perceptual learning* (Master's thesis). Graduate School of Engineering and Science, Bilkent University, Ankara, Turkey.
- Blurton, S. P., Feifel, J., & Gondan, M. (2023). Speeded response tasks with unpredictable deadlines. *Journal of Mathematical Psychology*, 115, Article 102776.
- Cicchini, G. M., Mikellidou, K., & Burr, D.C. (2024). Serial Dependence in Perception. *Annual Review of Psychology*, 75, 129–154.
- Citri, A., & Malenka, R.C. (2008). Synaptic plasticity: multiple forms, functions, and mechanisms. *Nature Reviews Neuroscience*, 9(11), 879–890.
- Crognale, M. A. (2002a). The maturation of color vision in humans. *Journal of Vision*, 2(4), 238–246.
- Crognale, M. A. (2002b). Development, maturation, and aging of chromatic visual pathways: VEP results. *Journal of Vision*, 2(6), 438–450.
- Dannemiller, J. L. (1988). The development of color perception in infants. *Developmental Psychology*, 24(6), 672–682.
- Dinse, H. R., & Merzenich, M. M. (2002). Adaptation of inputs in the somatosensory system. In M. Fahle & T. Poggio (Eds.), *Perceptual learning*. The MIT Press.
- Dobkins, K. R. (2009). Minimal color sensitivity in newborns. *Journal of Vision*, 9(12), 1509–1519.
- Elangovan, N., Tuite, P. J., & Konczak, J. (2018). Somatosensory training improves proprioception and untrained motor function in parkinson's disease. *Frontiers in Neurology*, 9, 1–10.
- Fahle, M., Edelman, S., & Poggio, T. (1995). Fast perceptual learning in hyperacuity. *Vision Research*, 35(21), 3003–3013.
- Fiorentini, A., & Berardi, N. (2002). Adaptation and learning in the visual perception of grating. In M. Fahle & T. Poggio (Eds.), *Perceptual learning*. The MIT Press.
- Fournier, D., & Teskey, G. C. (2014). Training-induced plasticity of the adult motor cortex. *Journal of Neuroscience Research*, 92(3), 351–357.
- Gilbert, C. D. (1998). Adult cortical dynamics. *Physiological Reviews*, 78(2), 467–485.
- Hamilton, H. K., & Mathalon, D. H. (2023). Probing long-term potentiation-like visual cortical plasticity in humans using repeated visual stimulation: Effects on visual evoked potentials. *Neuropsychopharmacology*, 48(1), 217–218.
- Hochstein, S., & Ahissar, M. (2002). View from the top: Hierarchies and reverse hierarchies in the visual system. *Neuron*, 36(5), 791–804.
- Horiuchi, S., & Nagai, T. (2024). Color discrimination repetition distorts color representations. *Scientific Reports*, 14, Article 9615.
- Irvine, D. R. F. (2018). Auditory perceptual learning and changes in the conceptualization of auditory cortex. *Hearing Research*, 366, 3–16.
- Jung, M. W., & Xie, Z. (2016). Plasticity of the adult brain: New insights from the molecular and cellular mechanisms. *Journal of Neuroscience Research*, 94(8), 758–772.
- Katsimpokis, D., Hawkins, G. E., & van Maanen, L. (2020). Not all speed-accuracy trade-off manipulations have the same psychological effect. *Computational Brain and Behavior*, 3(3), 252–268.
- Kawabata, M., Kawabata, Y., Sasaki, M., Takahashi, F., & Kasai, Y. (2020). The contributions of experience of artistic club activities to color discrimination for undergraduate revealed in 100 hue test evaluation method with reduced time limit. *Color Science Research*, 42, 163–174.
- Kawabata, Y., & Kawabata, M. (2014, March). Individual differences and skill for 100-hue discrimination in normal color vision. *The Journal of Cultural Sciences*, 636, 1124–1135.
- Kawato, M., Lu, Z. L., Sagi, D., Sasaki, Y., Yu, C., & Watanabe, T. (2014). Perceptual learning - the past, present and future. *Vision Research*, 99, 1–4.
- Knoblauch, K., Saunders, F., Kusuda, M., Hynes, R., Podgor, M., ... Monasterio, F. M. (1987). Age and illuminance effects in the Farnsworth-Munsell 100-hue test. *Applied Optics*, 26(8), 1441–1448.
- Knoblauch, K., Vital-Durand, F., & Barbur, J. (2001). Variation of chromatic sensitivity across the life span. *Vision Research*, 41(1), 23–36.
- Kurzawski, J. W., Lunghi, C., Biagi, L., Tosetti, M., Morrone, M. C., & Binda, P. (2022). Short-term plasticity in the human visual thalamus. *eLife*, 11, e74565.
- Lakowski, R. (1969). Theory and practice of color vision testing: a review. Part 2. *Occupational and Environmental Medicine*, 26, 265–288.
- Levelt, C. N., & Hübener, M. (2012). Critical-period plasticity in the visual cortex. *Annual Review of Neuroscience*, 35, 309–330.
- Levenson, J., Weeber, E., Selcher, J. C., Kategaya, L. S., Sweatt, J. D., & Eskin, A. (2002). Long-term potentiation and contextual fear conditioning increase neuronal glutamate uptake. *Nature Neuroscience*, 5, 155–161.

- Lidström, A. (2023). Serial dependence in facial identity perception and visual working memory. *Attention, Perception, & Psychophysics*, *85*(7), 2226–2241.
- Lunghi, C., Burr, D. C., & Morrone, M. C. (2013). Long-term effects of monocular deprivation revealed with binocular rivalry gratings modulated in luminance and in color. *Journal of Vision*, *13*(6), 1.
- Martin, S. J., Grimwood, P. D., & Morris, R. G. M. (2000). Synaptic Plasticity and Memory: An Evaluation of the Hypothesis. *Annual Review of Neuroscience*, *23*(1), 649–711.
- Morrone, M. C., Burr, D. C., & Fiorentini, A. (1990). Color vision and its development in children. *Vision Research*, *30*(7), 1107–1118.
- Ratcliff, R., & McKoon, G. (2008). The Diffusion Decision Model: Theory and Data for Two-Choice Decision Tasks. *Neural Computation*, *20*(4), 873–922.
- Rigby, H. S., Warren, B. F., Diamond, J., Carter, C., & Bradfield, J. W. (1991). Colour perception in pathologists: the Farnsworth-Munsell 100-hue test. *Journal of Clinical Pathology*, *44*(9), 745–748.
- Roberson, D., & Hanley, J. R. (2010). Relatively speaking: An account of the relationship between language and thought in the color domain. *Language and Cognitive Processes*, *25*(7–9), 964–991.
- Sasaki, Y., Nanez, J. E., & Watanabe, T. (2010). Advances in visual perceptual learning and plasticity. *Nature Reviews Neuroscience*, *11*, 53–60.
- Shevell, S. K., & Kingdom, F. A. (2008). Color in complex scenes. *Annual Review of Psychology*, *59*, 143–166.
- Teller, D. Y. (1998). Spatial and temporal aspects of infant color vision. *Vision Research*, *38*(21), 3275–3282.
- Teyler, T. J., & DiScenna, P. (1987). Long-term potentiation. *Annual Review of Neuroscience*, *10*, 131–161.
- Thierry, G., Athanasopoulos, P., Wiggert, A., Dering, B., & Kuipers, J. R. (2009). Unconscious effects of language-specific terminology on preattentive color perception. *Proceedings of the National Academy of Sciences*, *106*(11), 4567–4570.
- Wang, W. Y. (2021). A review of perceptual learning based on speed-accuracy tradeoff. *Advances in Psychology*, *11*(06), 1530–1538.
- Wang, Z., Kim, D., Pedroncelli, G., Sasaki, Y., & Watanabe, T. (2019). Reward evokes visual perceptual learning following reinforcement learning rules. *bioRxiv*, Article 760017. <https://doi.org/10.1101/760017>
- Widen, S. C., Russell, J. A., & Broesch, T. (2010). The development of color categorization in infants and children. *Cognitive Development*, *25*(2), 129–144.
- Yang, S., Ro, Y. M., Wong, E. K., & Lee, J. H. (2005). Color compensation for anomalous trichromats based on error score of FM-100 hue test. In Proceedings of the 27th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (pp. 6571–6574). IEEE.
- Yellott, J. I. (1971). Correction for fast guessing and the speed-accuracy tradeoff in choice reaction time. *Journal of Mathematical Psychology*, *8*, 159–199.
- Yuodelis, C., & Hendrickson, A. (1986). A qualitative and quantitative analysis of the human fovea during development. *Vision Research*, *26*(6), 847–855.