Fundamental Study of Color Combinations by Using Deuteranope-Simulation Filter for Controlling the Handicap of Color Vision Diversity in Video Games

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Abstract. Color video games are often disadvantageous for people with color blindness. Therefore, the game creator often supports them by displaying a color scheme suitable for a color vision type to solve this problem. However, it is difficult to say that the color scheme solves the handicap. Therefore, we aim to develop a mechanism that can control the advantages and disadvantages of people with color vision diversity and normal color vision by combining suitable colors. To examine color combinations that are difficult for people with normal color vision to discriminate and easy for people with color vision diversity we carried out an experiment using a Deuteranope-simulation filter. The results proved that there are color combinations that people with color vision diversity can easily discriminate. This means that the advantages of color vision and disadvantages of color vision diversity can be controlled appropriately by using color combinations.

Keywords: Color Vision Diversity, Deuteranope-Simulation Filter, Color Handicap.

1 Introduction

Nowadays, people recognize e-sports [1] as a sport, so the demand for online games is increasing rapidly [2]. As a result, a wide variety of players play online games with others every day. However, some players are disadvantaged by handicaps. Therefore, there needs to be a system that keeps games fair because handicaps complicate game elements related to auditory and visual senses. We focused on people with color vision diversity because about 5% of men and 0.2% of women in Japan had color vision diversity [6] in 2002.

People with color vision diversity see specific colors, such as red or green, differently from people with normal color vision [3]. Fig. 1 shows an example of visible colors for people with normal color vision and Deuteranope (a common color vision diversity) [4]. In this example, it is very difficult for people with Deuteranope to distinguish the blue one from the purple one and the yellow one from the green one. In video games, players must make judgments as quickly as other players. Therefore, players with normal color vision can easily overperform players with Deauteranope. If players with

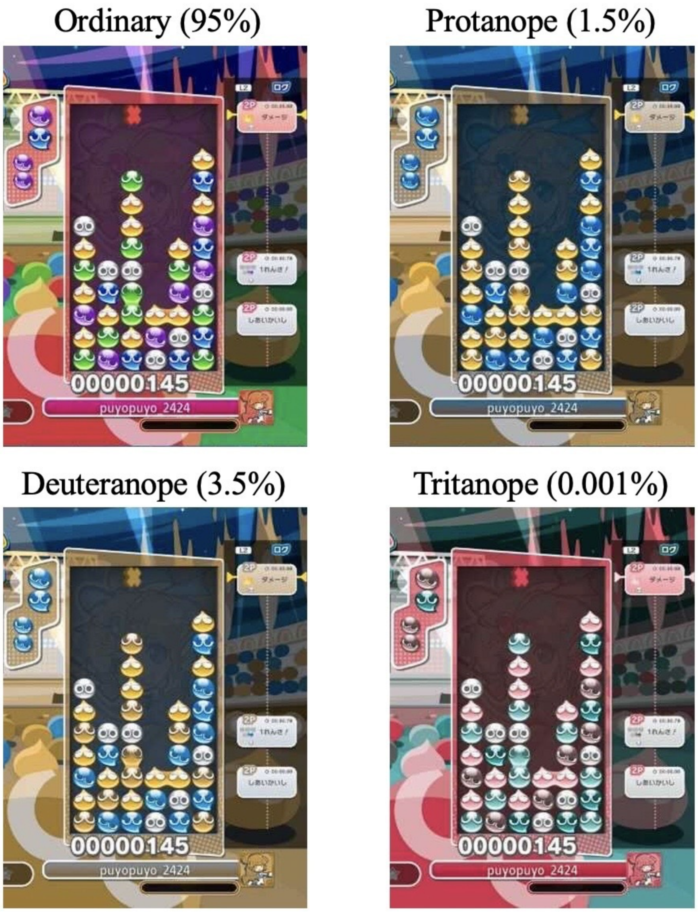

Fig. 1. An example of the Puyo Puyo seen by each color vision type and Rate in Japanese males. ©1991 SEGA Puyo Puyo

normal color vision can easily beat players with color vision diversity because of the game's color, that is not fair.

To solve the unfairness of playability of a game based on color vision diversity, several game companies implemented the function of color vision support. This function changes the color of objects in the game to enable players with color vision diversity to distinguish one color from another easily and quickly. However, such support sometimes doesn't work well. For example, color vision supports increase the playability of a specific type of color vision. However, this playability using color vision support does not reach the playability of players with normal color vision. Also, since there are multiple types of color vision, it is not easy to support all color vision diversities by using only color vision support (see Fig. 2).

With these issues in mind, we aim to eliminate color handicaps in people with color vision diversity with various characteristics. Specifically, this study investigates the possibility of controlling the advantages and disadvantages of color discrimination between people with normal color vision and people with color vision diversity (see Fig. 3). To realize a system that can control the handicap, we have to experiment to clarify which color combinations are easy and difficult for people with and without normal color vision to discriminate because there is no index to investigate the color combinations.

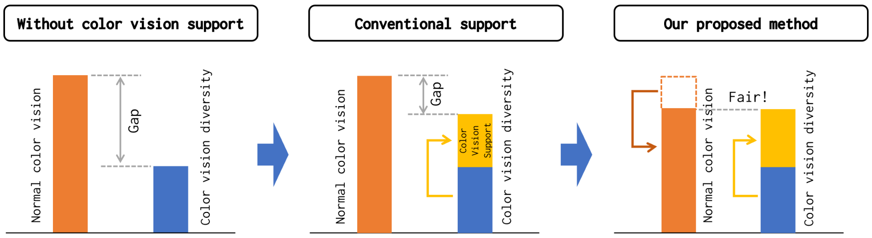

Fig. 2. Playability between a player with normal color vision and the other with color vision diversity in situation of without color vision support, with convensinoal color vision support and with our proposed method.

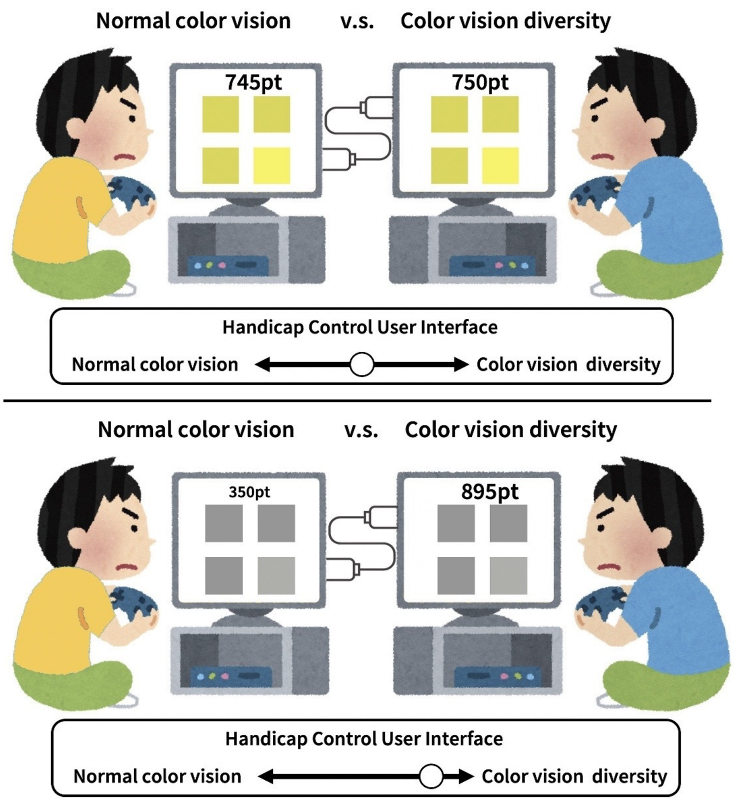

Fig. 3. Handicap control based on the type of color vision.

In this study, we focus on Deuteranope, a relatively common type of color vision diversity. We propose a method to investigate color as an index for controlling the advantages and disadvantages of different types of color vision. Specifically, in the experiment, participants with normal color vision use an optical Deuteranope-simulation filter to view a set of squares in which one square is a different color from the others and select the different colored square. This result will clarify which combinations of colors are easy to discriminate for people with Deuteranope and are difficult to discriminate for people with normal color vision.

The contribution of this paper is to propose a handicap control method that enables people with any color vision to play together in fairness and found an appropriate combination of colors by using color vision conversion filters.

2 Related Work

The symptoms of color vision diversity were initially clarified by Dalton [5] in 1798. We focused on people with color vision diversity because about 5% of men and 0.2% of women in Japan had color vision diversity [6] in 2002.

People with normal color vision have three normal pyramidal cells. In contrast, people with color vision diversity have a deficiency of these three pyramidal cells. Also, color appearance varies with cone cell defects and varies among individuals [7-9]. Therefore, people with color vision diversity are diverse and complex, and it is necessary to fully understand the factors of different patterns of color vision diversity. Then, it is essential to eliminate the handicap of color vision diversity in the video game by carrying out the color vision support suitable for each of them.

Okada et al. [7-9] proposed the concept of color universal design (CUD) [10]. However, prevalence is low [11] because people with diverse color vision have little opportunity to understand which colors are difficult to distinguish from other colors.

Thus, to overcome the fact that people with color vision diversity do not know how colors look, many types of research such as detection techniques and color vision simulation methods combine the difficult colors to distinguish. For example, from the viewpoint of CUD, Nakauchi et al. [12] researched a method to detect the difficult to discern colors for people with Protanope and Deuteranope and to correct them to discernible colors automatically. Also, Brettel et al. [13] simulated the appearance of a color on display in each color vision type, and Color Oracle [14] and Adobe Photoshop [15] can change the formation of a whole monitor by the color vision type. In this study, experiments were carried out to simulate the color on display, referring to the conversion calculation used in the method proposed by Asada [16].

There are several studies to support the daily lives of people with diverse color vision. Asada [16] developed an application to convert color in real time for each color vision type on an image seen through a camera. The technology is also suitable for business because it uses a smartphone that people usually mobile. Tanuwidjaja et al. [17] developed a Chroma system based on Google Glasses, a head mounted display. Chroma is a wearable system that can automatically convert visible color by the color vision type.

In addition to these systems for color vision correction, there are various other types of support. Ichikawa et al. [18] proposed a method to change the colors of Web pages for people with color vision diversity. This method decomposes the colors on a Web page into a hierarchy. It changes the colors from the positional relationship in the color space. Moreover, a color correction method based on still images [19] quantifies the degree of colors difficult to distinguish for people with color vision diversity to change the colors of all pixels. This method supports people with color vision diversity and a system that enables mutual compromise by providing complex colors for people with the normal color vision to discriminate.

3 Proposed System

To eliminate the handicap of color vision diversity, we examined color combinations that are easy to distinguish for each type of color vision diversity. We examined whether the color combinations were more suitable for video games for people with color vision diversity than for people with normal color vision. Because the population with color vision diversity is low depending on the type [9]. It is not easy to gather people with color vision diversity to conduct surveys and experiments on color perception.

This paper proposes a system to obtain an appropriate combination of colors by observing the difference between filtered and unfiltered conditions by applying a filter that simulates each color vision type and requiring users to select a target object from multiple objects accurately and quickly.

The procedures of this system for Deutereanopia are as follows:

1. The system randomly selects a combination of colors from color sets. Then, the system sets one color as the target color and the other as the basic color.
2. The system randomly selects one square as the target square from 36 squares arranged 6×6. Others are the basic squares (see Fig. 4).
3. The system randomly selects whether normal color vision mode or Deuteranopia color vision mode. If the Deuteranopia mode is selected, the system converts the target and basic colors to Deauteranope-simulated colors (see Fig. 5). In this conversion, we used the calculation proposed in [16] (see Fig. 6).
4. The system presents 35 basic squares using the basic color and one target square using the target color. If the system selected the Deuteranopia color vision mode, the system uses Deauteranope-simulated target color and Deauteranope-simulated basic color.
5. The system asks users to select a square that is different from the other squares as quickly as possible.
6. After the user’s selection, the system records the combination of colors, color vision mode, the target square’s position, the selected square, and the operation time.

By analyzing the recorded data, such as the error rates and the quickness, we can judge which combination of color is fair between people with normal color vision and

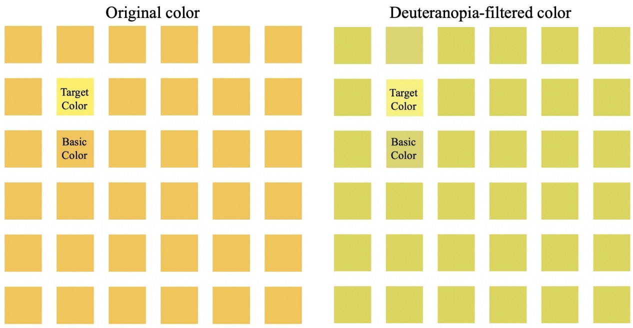

Fig. 4. Examples of target and basic colors in the normal color vision mode and the Deuteranopia color vision mode.

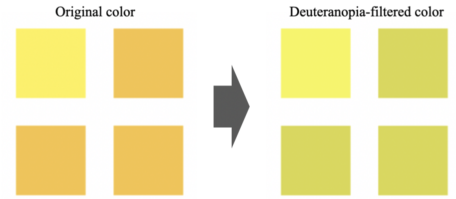

Fig. 5. Converting original colors (left) to Deuteranopia-filtered colors (right).

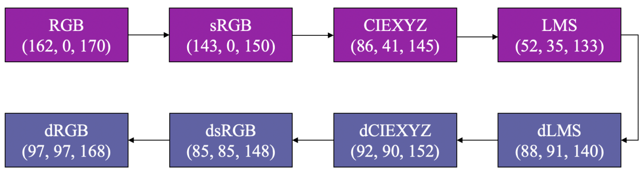

Fig. 6. Color conversion procedure of Deuteranopia filter used in this experiment. If the system changes dLMS for the other filter's one, the system is able to support the other color vision diversity.

people with diverse color vision. In addition, we can apply this for other types of color vision diversity by changing dLMS with others.

4 Experiment

4.1 Outline of the Experiment

To eliminate the vision based handicap that people with color vision diversity have when playing video games, this study aims to clarify the combinations of easy colors for people with color blindness to distinguish and difficult for people with normal color vision to determine. Since there are various types of color vision diversity, this study focuses on Deuteranope, one of the most common types.

Yamanaka et al. investigated different colors' visibility on Web pages for people with diverse color vision [20]. As a result, they found that the higher the lightness difference between the character and background colors, the higher the text visibility is. Therefore, this study tested the following hypothesis: the more significant the difference in lightness in color combinations are, the more accurately and rapidly people with color vision diversity can judge color differences are.

To choose the combinations of colors for this experiment, we conducted a preliminary test before this experiment test. We prepared 22 combinations of colors in this preliminary test and asked five participants to try this test. From the preliminary test results, we selected the combinations of target and basic colors (see Table 1). Table 1 also shows the Deauteranope-filtered target color and basic color.

In the experiment, the number of trials in each task is 28 (combinations of colors per 1 condition) × 2 (conditions with and without a filter) = 56 trials. In addition, we ask participants to try 10 tasks. A trial finishes right after the participant clicks a square. Even if the clicked square was not the target, the system advanced to the next trial.

We recruited 13 participants (five men and eight women) with normal color vision in this experiment. We conducted a color vision check based on the Ishihara color vision test table [21] in advance and confirmed that no participants had color vision diversity. Moreover, before the experiment, the participants were told to stay 50 cm away from the display, not lean forward during the investigation, and prioritize accuracy over speed selection.

4.2 Experimental Results

One participant who was an outlier (mean ± 2 standard deviations) in both the correct answer rate and answer time was excluded in analyzing the experimental results. So, we used the experimental results of 12 participants (5 men and 7 women) to analyze.

Table 1 shows the correct answer rates for 12 participants in each color combination. The paired t-tests for the correct response rates of filtered and unfiltered conditions showed a significant difference of $p < 0.05$ for five pairs (pair-5, pair-8, pair-13, pair-24, pair-27) and $p < 0.01$ for ten pairs (pair-7, pair-9, pair-10, pair-17, pair-18, pair-22, pair-23, pair-25, pair-26, pair-28) of the 28 color combinations. Of the 15 color combinations that showed significant differences, the correct color combinations in the filtered condition were pair-5, pair-7, pair-8, pair-13, pair-22, and pair-24.

Next, we performed a paired t-test on the response time. Of the 19 color combinations that showed significant differences, six pairs had shorter mean response times in the filtered condition; pair-3, pair-6, pair-7, pair-8, pair-14, and pair-24.

Table 2 shows the percentage of correct answers and the average response time of the 12 participants in filtered and unfiltered conditions. From Table 2, the overall correct answer rate was higher. The average response time was shorter in the filtered condition (correct answer rate is 0.70 and response time is 5.26 seconds) than in the unfiltered state (correct answer rate is 0.80 and response time is 6.27 seconds).

Table 1. Percentage of correct responses and average response time with color combinations (RGB) and no filters.

	Target Color	Basic Color	Unfiltered		Filtered		Unfiltered correct answer rate	Filtered correct answer rate	Unfiltered response time	Filtered response time
			Target	Basic	Target	Basic				
pair-1	171, 145, 0	204, 167, 0					0.99	0.95	1.35	1.59
pair-2	204, 167, 0	171, 145, 0					0.98	1.00	1.42	1.68
pair-3	171, 30, 85	164, 38, 92					0.74	0.80	6.50	5.09
pair-4	164, 38, 92	171, 30, 85					0.72	0.81	5.99	7.47
pair-5	165, 0, 171	180, 0, 204					0.88	0.95	2.97	2.13
pair-6	180, 0, 204	165, 0, 171					0.88	0.94	2.62	1.85
pair-7	230, 138, 184	232, 139, 190					0.15	0.68	10.14	7.20
pair-8	232, 139, 190	230, 138, 184					0.38	0.62	14.75	6.61
pair-9	90, 64, 89	98, 55, 85					0.98	0.36	2.29	12.26
pair-10	98, 55, 85	90, 64, 89					0.98	0.25	1.82	13.20
pair-11	0, 180, 147	0, 210, 167					1.00	0.98	1.82	1.71
pair-12	0, 210, 167	0, 180, 147					0.96	0.95	2.36	2.21
pair-13	154, 227, 82	141, 217, 98					0.83	0.94	3.30	2.90
pair-14	141, 217, 98	0, 210, 167					0.82	0.83	3.56	3.83
pair-15	199, 35, 230	172, 49, 185					0.93	0.97	1.94	2.01
pair-16	172, 49, 185	199, 35, 230					0.97	0.99	1.76	1.54
pair-17	145, 165, 0	135, 168, 0					0.93	0.02	2.84	33.72
pair-18	135, 168, 0	145, 165, 0					0.97	0.05	2.96	7.62
pair-19	0, 0, 168	0, 2, 143					0.91	0.92	2.86	2.91
pair-20	0, 2, 143	0, 0, 168					0.84	0.79	4.78	4.57
pair-21	186, 0, 112	180, 30, 105					0.50	0.56	8.99	9.53
pair-22	180, 30, 105	186, 0, 112					0.33	0.53	11.84	9.49
pair-23	0, 157, 168	0, 149, 161					0.59	0.37	7.74	9.77
pair-24	0, 149, 161	0, 157, 168					0.29	0.47	10.17	8.08
pair-25	99, 94, 0	115, 101, 0					0.97	0.71	2.32	7.27
pair-26	115, 101, 0	99, 94, 0					0.98	0.75	1.93	5.03
pair-27	115, 0, 0	99, 0, 0					0.97	0.84	2.80	5.33
pair-28	99, 0, 0	115, 0, 0					0.83	0.60	4.13	7.36

5 Discussion

In this study, we hypothesized the more significant the difference in lightness in a combination of colors is, the more accurately and quickly a person with color vision diversity can judge the color difference. For this purpose, we examined which color combinations are easy for people with color vision diversity to distinguish. In video games, players must make accurate and quick judgments, often regarding color, to win. Therefore, this experiment focuses on color combinations. The correct answer rate was over 0.7, and the average response time was 6 seconds or less in both filtered and unfiltered varieties. Note that the appropriate correct answer rate and the response time are depending on the game type. We can easily change the threshold of the correct answer rate and the response time easily depending on the game's type, such as shootings, fighting games, puzzles, and so on.

Fig. 7 and 8 show combinations of colors with short average response times in unfiltered and filtered conditions. Among these color combinations, we examine pair-

Table 2. Correct response rate and average response time for 12 participants.

	Correct answer rate	Average response time (sec)
Filtered	0.70	7.29
Unfiltered	0.80	5.26
All	0.75	6.27

Table 3. HSV with and without filters.

	Target Color Unfiltered	Basic Color Unfiltered	Target Color Filtered	Basic Color Filtered
pair-5	297, 100, 67	292, 100, 80	240, 42, 66	240, 46, 79
pair-6	292, 100, 80	297, 100, 67	240, 46, 79	240, 42, 66
pair-11	169, 100, 70	167, 100, 82	60, 0, 58	60, 0, 58
pair-15	290, 84, 90	294, 73, 72	240, 46, 89	240, 39, 71
pair-26	52, 100, 45	56, 100, 38	60, 100, 41	60, 100, 37
pair-27	0, 100, 45	0, 100, 38	60, 100, 26	60, 100, 22

5, pair-6, pair-26, and pair-27, which showed significant differences in the mean response time, and pairs-11 and pair-15, which showed small differences in the mean response time.

According to Table 1 and Fig. 8, pair-5 and pair-6 had the correct answer rates higher than 0.85 in both conditions and shorter average response times in the filtered state than in the unfiltered condition. Here, to examine whether these color combinations are easy for people with color vision diversity to discriminate, RGB of pair-5 and pair-6 was converted into HSV. HSV is a color space consisting of hue, saturation, and value. Table 3 shows the results of converting RGB into HSV for the color combinations discussed in this chapter. From Table 3, the comparison of HSV of the target and basic colors for the filtered and unfiltered conditions shows that the difference in lightness between the target and basic colors is equal in both states. However, the saturation value is different in the filtered shape.

On the other hand, HSV in the unfiltered condition showed a slight difference in hue values between the target and basic colors. From these results, combinations of colors that are easier for people with Deuteranope to discriminate need different values of Chroma and lightness but the same hue values. However, there is a 6~7% difference in the percentage of correct answers, which needs to narrow slightly.

Next, Fig. 7 shows that pair-26 and pair-27 have shorter average response times in the unfiltered condition than in the filtered state. Therefore, these combinations are considered difficult for people with color vision diversity to discriminate. Table 3 shows that the target color is lighter than the basic color in both the filtered and

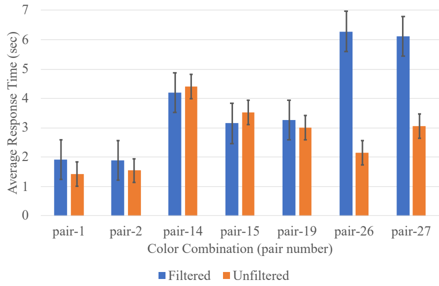

Fig. 7. Combinations of colors with short average response times in unfiltered conditions.

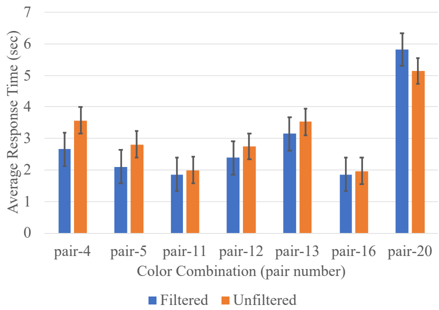

Fig. 8. Combinations of colors with short average response times in filtered conditions.

Table 4. Advantageous and disadvantageous color combinations for general and Deuteranope.

	General advantage	General disadvantage
Deuteranope advantage	pair-11, pair-15	pair-5, pair-6
Deuteranope disadvantage	pair-25, pair-26	pair-19

unfiltered conditions. Here, the colors that are easy for people with color vision diversity to discriminate can accurately discriminate regardless of the use of the filter. The response time is shorter in the filtered condition than in the unfiltered state. However, for pair-26 and pair-27, the unfiltered condition is unsuitable for people with color vision diversity because the average response time is much shorter than in the filtered state.

For pair-11 and pair-15, there was not much difference in the average response time between the filtered and unfiltered conditions in Fig. 7 and Fig. 8. Table 3 shows that the target color is lighter than the basic color. These color combinations are easy to discern for people with normal color vision and color vision diversity, so that these color combinations may remove the handicap of color vision diversity.

The above results clarify that people with Deuteranope can discriminate the target color when its lightness is higher than or equal to the surrounding color. These results support this paper's hypothesis: The more significant the difference in lightness in a combination of colors are, the more accurately, and quickly a person with color vision diversity can judge the color difference. Moreover, the results prove that lightness is a more critical element for color discrimination for people with color vision diversity than people with normal color vision. Furthermore, the results demonstrate that fair colors are easy to discriminate for people with normal color vision and color vision diversity when the target color has higher lightness than the circumference color. Table 4 shows the color combinations that are advantageous and disadvantageous for people with normal color vision and those with Deuteranope.

6 Summary

This study aims to eliminate the handicap of color perception that people with color vision diversity feel when they play video games. Colors that are easy for people with Deuteranope to discriminate are investigated based on the following hypothesis: The larger the difference in lightness in a combination of colors are, the more accurately and quickly a person with color vision diversity can judge the color difference. Specifically, we used a Deuteranope-simulation filter to convert normal color vision into a Deuteranope view in an experiment. Then, participants selected a different color target among alternatives with and without using the Deuteranope-simulation filter. The experimental results indicate that a combination of colors with different lightness values and saturation but the same hue value are easy to discriminate for people with color vision diversity.

We will examine a technique that controls the advantages and disadvantages between normal color vision and color vision diversity in future work. Specifically, video games should design using easy colors for people with color vision diversity to discriminate. In addition, we think it should be possible to enlighten people with the normal color vision about the differences in color appearance for people with color vision diversity. Moreover, we will find the appropriate correct answer rate and the response time depending on the game type, such as shooting, fighting, puzzle, and so on.

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