Development of a Digital Learning Game with Preliminary Screening for Congenital Color Vision Deficiency

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Abstract— **It is advisable to perform color vision screening tests in Japanese schools during the lower grades of elementary school and the first and second years of junior high school. This would allow schools to appropriately meet the needs from elementary school pupils in lower grades and junior high school students to avoid troubles when advancing to higher education or finding a job. However, guardians or parents' understanding of color vision screening tests is crucial since the screening tests in schools are conducted only upon their "requests." The "color vision education leaflets" issued by the Japan Society of School Health and the Japan Ophthalmologists Association are aimed at promoting the understanding of the screening tests. This research develops a digital learning game that can be used in color vision education for elementary school students and their guardians and also has the feature of color vision screening. This paper focuses on the "difficulty in identifying certain color combinations instantaneously," which afflicts people with color weakness. This was incorporated in the digital learning game as the feature for the screening test. Furthermore, it was confirmed through experiment verification that the feature is effective as a preliminary screening test.**

Index Terms—color vision, color blandness, color universal design

I. Introduction

In the human body, there are three cones with different spectral characteristics. These cones have visual cells that perceive the red, green and blue colors, respectively. People with these three types of visual cells are called people with normal color vision. As for people with one of the three types of visual cells missing, they are called people with dichromatic color vision (or color blindness). As for the case where the three types of visual cells are present, but one of them has reduced functionality, it is called anomalous trichromatic vision (or color weakness). If the visual cells that perceive the red color have a low degree of perception, it is called type 1 trichromacy. If the visual cells that perceive the green color have a low degree of perception, it is called type 2 trichromacy. If the visual cells that perceive the blue color have a low degree of perception, it is called type 3 trichromacy. Most people with congenital color weakness have type 1 or type 2 trichromacy, while type 3 trichromacy is rare. As for the percentage of people with color weakness, 5% of all Japanese males and 0.2% of Japanese females have color weakness. In the USA, 8% to 10% of males have it, while in Africa, 2% to 4% of males have it. The subjects of this research are people with anomalous trichromacy.

In accordance with the School Health and Safety Act (the School Health Act was renamed the School Health and Safety Act on April 1, 2009), the educational institutions in Japan conduct medical checkups for students annually. Until 2002, color vision tests were included in the mandatory items in medical examinations and were conducted annually for the children who reached the fourth grade of elementary school. However, in 2003, color vision tests were removed from the mandatory items in medical examinations by what was called the School Health Act amendment at the time. The color vision tests were conducted as exceptional procedures for those who desired it. However, at that point in time, color vision tests for young students were eliminated in effect. Underlying were social problems such as young students with congenital color vision anomalies facing discrimination due to problems related to color vision or suffering from disadvantages. As a result, around 2010, there emerged problems such as a problem in which middle or high school students do not know that they have a color vision anomaly until they start pursuing higher education or finding a job and have to change their life paths. This coincided with the timing of the students of the first generation after the elimination of color vision tests becoming high school students. Therefore, the society started questioning whether they should conduct color vision tests again. In response to that situation, the School Health and Safety Act was amended in 2014 and the matter of handling color vision tests was to be reviewed. Since 2016, the decision to conduct color vision tests has been up to each local government and each school and color vision tests were revived in effect in Japan. The schools that implement the tests conduct a thorough "questionnaire for color vision tests for young students" targeted at guardians while adequately protecting the privacy of the people undergoing these tests [1-5].

The color vision test in Japanese schools is a mere screening, and the actual test is left to medical institutions. Guardians' understanding and teaching staff's proper handling of children and parents are crucial in conducting the screening tests at schools. Therefore, the Japan Society of School Health and the Japan Ophthalmologists Association issued "color vision education leaflets." In Japan, there are educational activities for disseminating the characteristics of color vision deficiency and what kind of care is required for color-blind people in school and at home, in order to promote color vision screening. In this study, we have developed a digital learning game aimed at contributing to such educational activities. We have developed a digital learning game with preliminary screening for color vision deficiency, taking into account the situation of Japanese color vision problems. In this paper, we focused on the fact that people with imperfect color vision "have difficulty in swiftly identifying specific color combinations," and utilized this characteristic in events in that game, so that people with imperfect color vision would play the game

Received July 28, 2020, Accepted August 23, 2020, Published online December 6, 2020.

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for a longer period of time than normal people. This serves as the screening function. This paper mentions a verification experiment carried out for the purpose of checking whether the developed digital learning game is effective for preliminary color vision screening.

II. Current Situation of Color Vision Screening in Japan

In Japan, color vision screening was discontinued in 2003 and resumed in 2016, as mentioned in the previous section. Figure 1 shows the procedure for color vision screening in school after the resumption. After the resumption, a survey for checking whether guardians demand color vision screening was started. The procedure based on the guidelines by Japan Ophthalmologists Association is as follows [6].

- Step 1: To survey the demand from guardians of target students, such as second graders, first-year junior high school students, and first-year high school students. To distribute survey sheets to guardians of students for explaining color vision screening and asking whether they want the students to undergo the screening.
- Step 2: To conduct the screening targeting the students who demanded color vision screening in school. It is recommended to use “14 tables of the concise version of Ishihara Color Vision Testing Table II” during the screening. It is globally common to use Ishihara Color Vision Testing Table for color vision screening [7].
- Step 3: To encourage students who are suspected of having color vision deficiency to go to an ophthalmic hospital for a detailed examination [8, 9].
- Step 4: If a student is diagnosed as having color vision deficiency at an ophthalmic hospital, the student and his/her guardian will receive guidance about what they should care in school, etc. Then, the guardian will submit the results of diagnosis at the hospital and the report including what they should care in the school to the student’s school.
- Step 5: With reference to the submitted documents, the school gives appropriate instructions and necessary support to the student.

At Step 1, it is necessary to pay attention to students who did not demand color vision screening. There is a case in which such students advance from elementary school to middle/high school without noticing his/her congenital color vision deficiency and face a difficulty due to his/her color vision deficiency when finding a job or going on to college. School education is supposed to avoid such a case and provide students with sufficient time to think over their career paths. To do so, the color vision screening at Step 1 is important, and it is important to provide guardians with information about color blindness in society as Step 0. This study is an activity between Step 0 and Step1.

Nakada et al. reported on the current situation of the number of students demanding color vision screening in Japan [10]. That surveyed and researched the current situation of color vision screening and effects of measures in schools in Sapporo City, Hokkaido. According to that report, the number of guardians of second graders demanding color vision screening was surveyed in Sapporo City in 2016, and it was found that 1,274 (52.3%) out of 2,438 respondents were demanding color vision screening. Around half of them demanded color vision screening, but the number is not so large. This result indicates that it is essential to promote educational activities regarding color vision screening.

It is necessary to not only make color vision screening known by more people, but also establish a diverse society tolerant of color vision deficiency. Having a color vision anomaly only means that a person has a color vision that causes him/her to have difficulty distinguishing some colors. Moreover, the misperception of a color varies among color-blind people, hence the problem cannot be solved just by substituting a specific color with another. Color Vision Barrier-Free Design (hereinafter referred to as “Color Universal Design”) is the design of products that takes into consideration the color vision diversity to prevent people with color weakness from misperceiving colors and make sure that the information is conveyed accurately to everyone. Moreover, a lot of efforts related to color vision diversity were made by Kei Ito (currently a professor at the University of Tokyo) and Masataka Okabe (currently a professor at the Jikei University School of Medicine). In 2004, they established an NPO called Color Universal Design Organization that continues to disseminate information on how to create a society that takes into consideration color vision diversity. Also, companies, administrations and associations joined Color Universal Design Organization, and the committee for producing a set of color combinations recommended by Color Universal Design was established in 2007. This committee facilitates the research, development and dissemination of the printed, painted and display screen versions of “Set of Color Combinations Recommended by Color Universal Design” [11,12]. In Japan, information is transmitted in public places in an improved way so that there is no substantial gap in information received no matter whether the person is in a color vision majority or minority. When creating products and services, special designs suited for people with color weakness are not prioritized, but they use colors in a manner that takes into consideration the various types of color vision among users. Thus, the approach of creating products and services that pursue a color arrangement considering the diversity in color vision among users can also be regarded as one of the trends of design thinking.

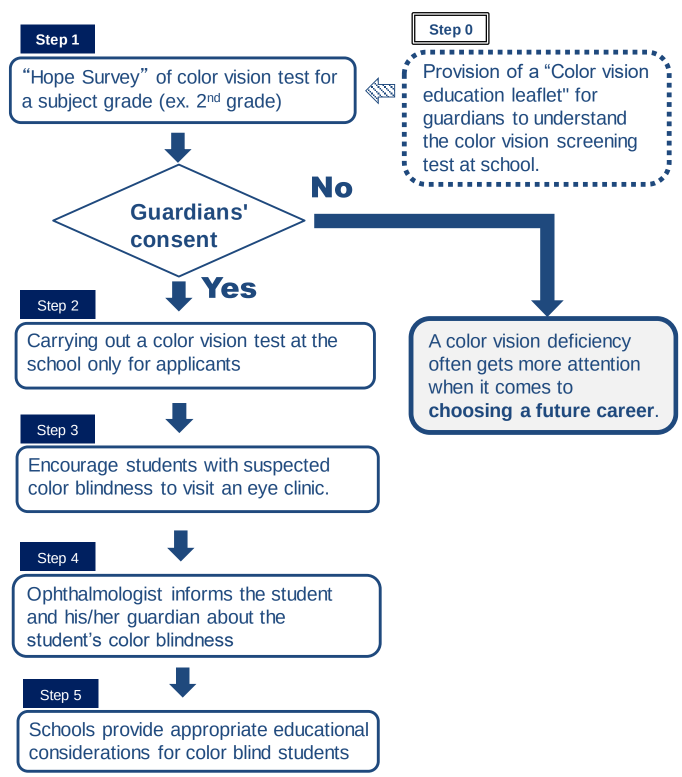


Fig. 1. Care for students with color blindness in Japan. Here, the procedure made with reference to the recommendations of the Japan Ophthalmologists Association is introduced.

III. Experiments Investigating the Effects of Game Design Factors

A. Research into the Inconvenience for Color-Blind People and their Worries in their Daily Lives

Through the distribution of PCs, opportunities to judge "information according to color differences" increased rapidly. Therefore, it became necessary to consider the visibility of color blindness in the manufacturing field, and a check tool for understanding how color-blind people sense colors (or face difficulty in distinguishing colors) has been put into practice. The check tool developed by Maekawa, et al. was adopted for the displays of EIZO Corporation and the software of Adobe Systems Inc. (Adobe Photoshop and Adobe Illustrator). By using them, normal people can virtually experience "what kinds of colorations are difficult to distinguish for color-blind people" [13]. In addition, web browsers, such as Google Chrome, are equipped with a color weakness simulator as an extended function, and this is an effective check tool for website design. Furthermore, portable check tools include the smartphone app "Color Simulator" developed by Asada [14] and the eyeglasses for virtually experiencing color weakness "Variantor" of Itoh Optical Industrial Co., Ltd. [15].

In this study, how color-blind people perceive colors in their daily lives were studied, in order to design software for detecting color weakness. Since the research was conducted while walking, the eyeglasses for virtually experiencing color weakness were used considering safety. After obtaining permission from the staff of a shopping mall in the vicinity of the university, we walked while wearing the eyeglasses inside the shopping mall (Fig. 2). For example, it was found that the location of a fire extinguisher shown in an emergency escape map is difficult to see.

From this on-site research, we confirmed the necessity to support the visibility of color-blind people by utilizing not only colors, but also symbols and indices, for information to distinguish. However, it was also found that they cannot distinguish colors based on indices and symbols in a blink, and that it is difficult to convey information with them. We considered that it is possible to realize the detection function by adding a program for assisting color-blind people in distinguishing colors in a blink, when designing color vision screening software. Since color vision screening is targeted at children in the lower grades of elementary school, we decided to utilize a digital game for testing color vision while giving the pupils enjoyment.

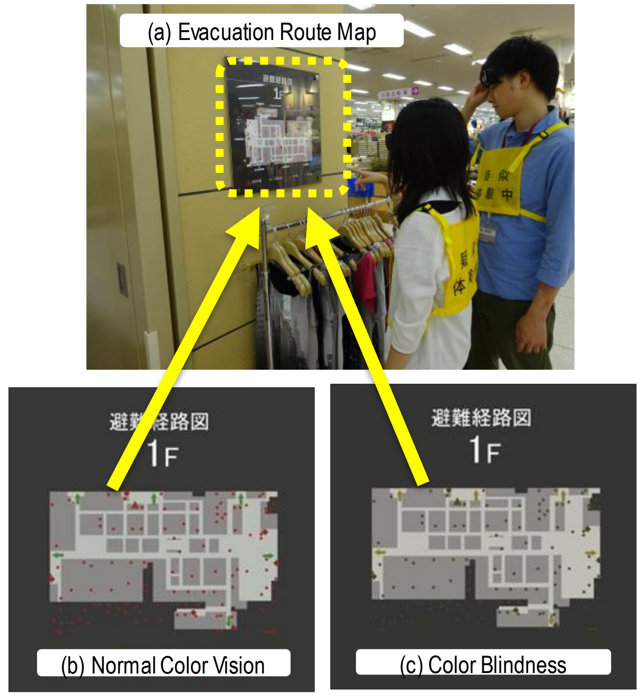


Fig. 2. Experience: (a) We tried walking inside the facility with Variantor and checked the evacuation route map. (b) The red dots show fire extinguisher facility location. (c) The evacuation route map as seen by a person with color vision deficiency was created using the color vision deficiency simulation function of Adobe Photoshop CC.

B. Prototype of a Digital Learning Game with a Color Vision Screening Function

In this study, we develop a digital learning game while expecting that it will motivate game players to undergo the screening test for color blindness, if they are not aware of color weakness [16,17]. The game will have the following features.

- The game can be enjoyed by anyone, including normal color vision people and color-blind ones.
- Target players are kindergarteners and children in the lower grades of elementary school.
- The game can be played with various devices, including tablet terminals and desktop PCs.

1) Shooting game development

This is a conventional 2-dimensional shooting game. One can move in all directions and shoot by operating the system. We prepared two types of ammunition for enemy attacks. One type of ammunition is red (RGB color code: 255.0.0), and the other is yellow (RGB color code: 255.255.0). The background color is set to be brown (RGB color code: 93.85.36). Due to this, people with color vision deficiency will have a

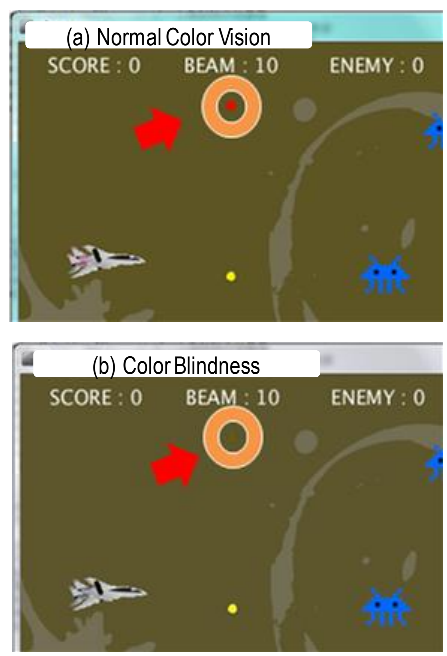


Fig. 3. The figure shows a screenshot of the shooting game. The above image (a) is for normal color vision, while the lower image (b) is for color blindness. The red ammunition is pointed by the arrow in the figure. Due to this, people with color vision deficiency will have a hard time discriminating the red ammunition because it will blend into the background.

hard time discriminating the red ammunition because it will blend into the background. The attacks from the enemy are set so that both red and yellow ammunition will be shot simultaneously. A person with color vision deficiency will tend to deal with only the yellow ammunition during play, and this action by the game player will indicate the possibility of the player having color vision deficiency. Fig. 3 is a screenshot of the shooting game. The red ammunition is pointed by the arrow in the figure.

We submitted the prototype shooting game to the festival of a junior high school in Kanazawa city in Nov. 2014. The aim was to find out if the digital learning game can be enjoyed by a junior high schooler, whether they have color vision deficiency or not. In other words, we confirmed its entertainment characteristics. Therefore, we did not give instructions about color vision to the game players. We considered that by letting them know, they may not enjoy the game as much. Therefore, junior high schoolers who simply wanted to enjoy games participated. The game received high marks from junior high schoolers, and many played the game multiple times. Most of them gave positive opinions, such as the opinion that they "enjoyed" the game. Also, the degree of difficulty was evaluated as "just right," and so we concluded that it is appropriate.

The game was played by mainly male students, and there was a possibility that 5% had color vision deficiency. However, we did not find anyone who had discomfort about discriminating the two colors. We observed them when they played games, and we feel that it would be difficult to find players with color vision deficiency during game play. The reason for this is that compared to other types of games, shooting game players operate their system according to split-second decisions in the game field. Therefore, it would be difficult to discriminate between "simple operation errors" and "delays caused by color vision."

2) Mazing game development

The player's ball is located in the center and two colored balls (red and blue), which will serve as a guide through the maze, are located at the start point (Fig. 4). The player selects one of the balls to use it as a guide, and follows the ball until they reach the goal. When a red or blue ball is on a gray background, people with normal color vision will notice the red ball first. On the other hand, people with color vision deficiency will have a hard time visually recognizing the red ball, and will select the blue ball. We will detect the possibility of a game player having color vision deficiency by using this mechanism. Since this is a maze game with guides, a wide target age range can be assumed.

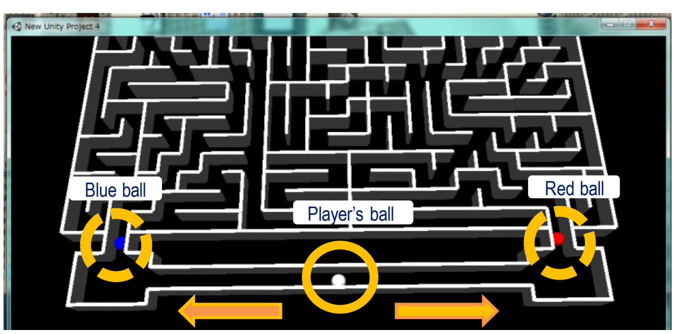


Fig. 4. A conventional two-dimensional maze game. The player's ball is located in the center and two colored balls (red and blue), which will serve as a guide through the maze, are located at the start point. The player selects one of the balls to use it as a guide.

We exhibited the maze game at a "civil science awareness event" sponsored by the local government in Dec. 2014. All who experienced the maze game judged that the game is enjoyable. The pre-schoolers and grade schoolers said that they "enjoyed following the ball." However, the pre-schoolers not only played the game once, but wanted to play it the second time. They tended to select a different color ball from the one they selected first. The maze game will be improved and configured to have multiple screens, and players will be able to enjoy the game by selecting a ball for each of the screen. We feel that we may be able to find people suspected of having color anomaly by recording the guide balls they selected during the game. It has been found to be effective to incorporate a mechanism related to color screening as a "guide" for advancing in a game.

IV. Development of Digital Learning Game for Screening Color Blindness

From the surveys and trial experiments in the previous section,, the following conditions are crucial factors in the proposed game in order to detect color blindness.

- As a student plays the game, there are components embedded to detect color blindness.
- The game will not be over by the player's inadvertent wrong operation or mistake.

The proposed action game incorporates the two conditions stated above. The produced digital learning game is an ordinary two-dimensional action game. Players move their characters by using the right, left, and space keys, and compete for controlling events in the game (Fig. 5). The game is constituted by 7 stages in the first half and 7 stages in the second half. For all of the stages, a "guide" is displayed so that characters can proceed to the next stage. By effectively using this guide, game players can overcome all of the 14 stages in a short period of time. For the 7 guides used for the 7 stages in the first half, color combinations that are difficult to distinguish for color-blind people are used. For the 7 guides used for the 7 stages in the second half, color combinations that are easy to distinguish for color-blind people are used. Fig. 6 shows one example. Fig. 7 shows the guides used for each stage. These color combinations were determined with reference to "Set of color combinations recommended by Color Universal Design" by the committee for producing the set of color combinations recommended by Color Universal Design. In the guide shown in Fig. 7, the upper guides (a) are difficult for people with color blindness to recognize. On the other hand, the guides at the bottom (b) can be recognized relatively easily by people with color blindness.

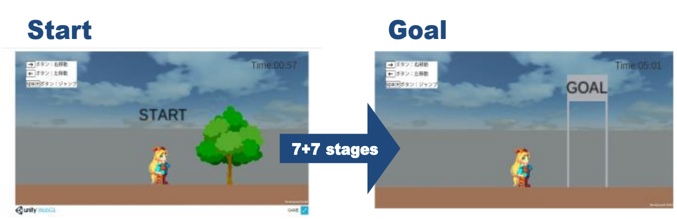


Fig. 5. The figure shows a screenshot of the action game. The game is constituted by 7 events in the first half and 7 events in the second half.

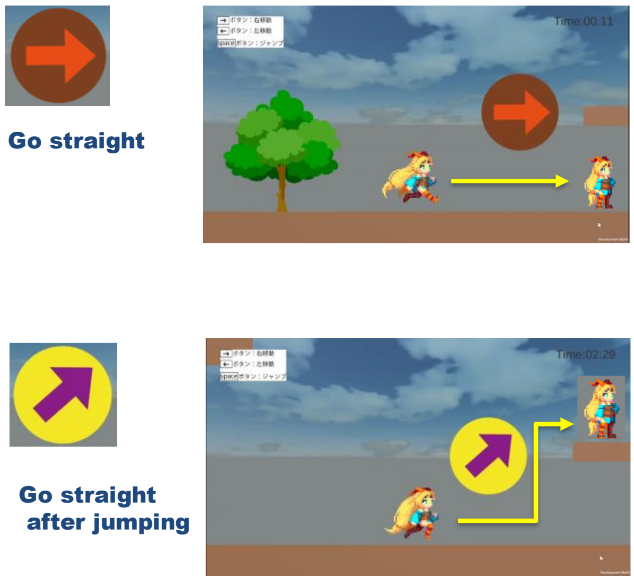
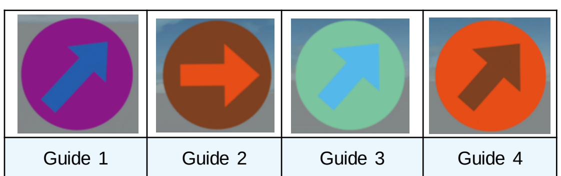
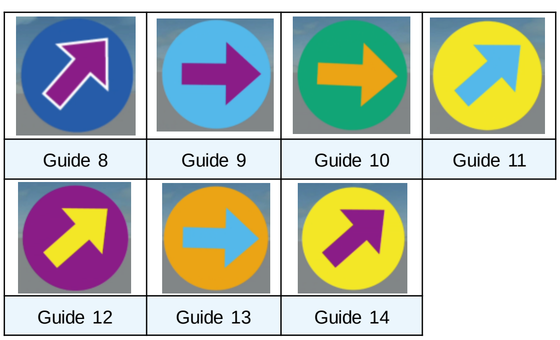


Fig. 6. At each stage, a “guide” will be displayed to help the character proceed to the next stage. The guide at the top is easy to see for students with color weakness. However, the guide at the bottom is difficult to see for students with color weakness.



(a) The 7 guides are used from Stage 1 to Stage 7 in this action game.



(b) The 7 guides are used from Stage 8 to Stage 14 in this action game.

Fig. 7. List of guides used in this action game. The upper guides are difficult to recognize for color-blind people. On the other hand, the lower guides are recognized relatively easily by color-blind people.

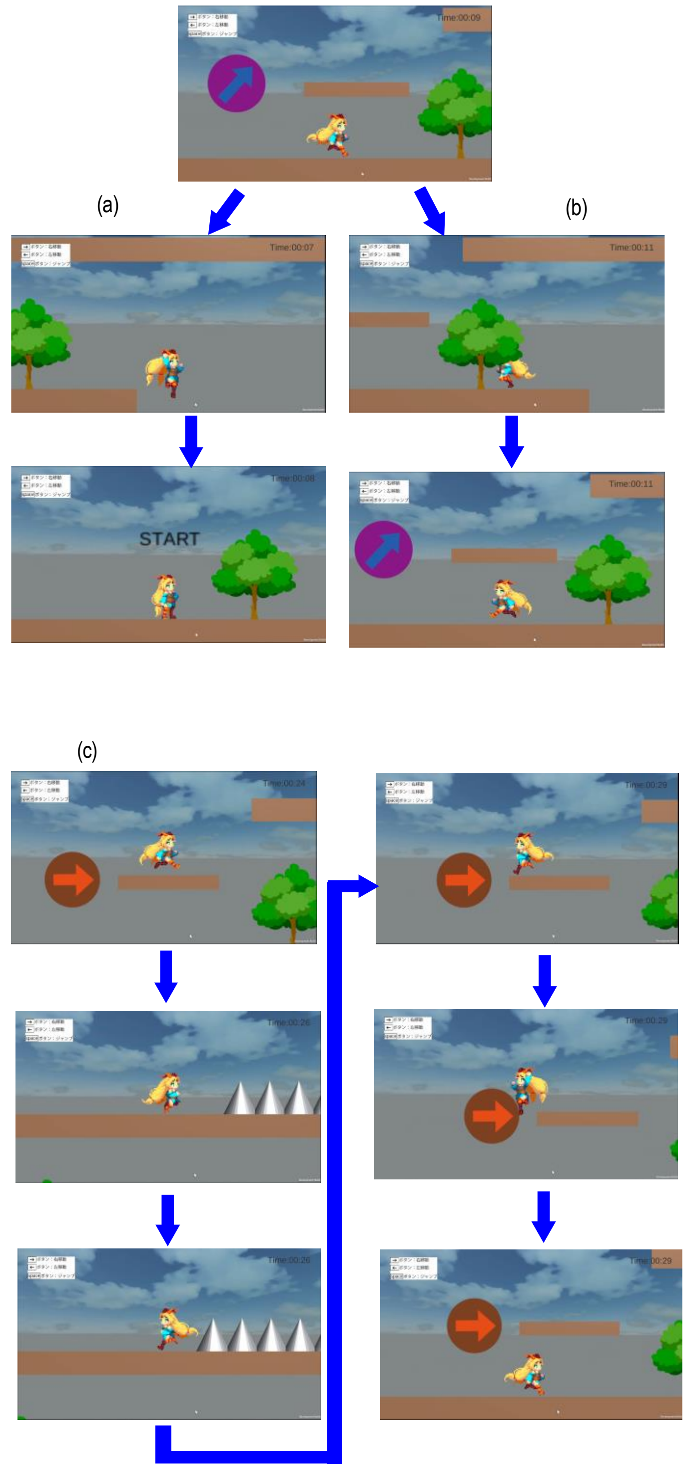


Fig. 8. The figure shows what happens when the player advances the character in a different direction from the guide's support. (a): It shows a character falling off a cliff and returning to the start point. (b): It shows the character returning to the road she came to because she found a cliff. (c): It is when the character returns to the path she came to because she found some obstacle.

During game play, a guide moves as a character moves, so there are some cases in which a color-blind person cannot notice a guide and the guide does not function. Fig. 8 shows what happens when the player advances the character in a different direction from the guide's support. Fig. 8 (a) shows a character falling off a cliff and returning to the start point. On the other hand, Fig. 8 (b) shows the character returning to the road she came to because she found a cliff. Also Fig. 8 (c) shows a scene in which the character returns to the path she came to because she found some obstacle. In this way, if the player does not use the guide well, the time it takes to reach the goal will increase. If a player repeats this situation without operating mistakes, it is suspected that the player is color blind.

The produced action game was exhibited at a municipality's event held in the vicinity of our college in Dec. 2019. That event was for citizens, and visitors were composed of mainly local students of elementary and middle schools. Before starting each experiment, we explained the research to subjects (elementary school students) and their guardians in writing and orally and obtained the guardians' consent, in accordance with the instructions from the Kanazawa Institute of Technology's committee exclusively for checking the ethics of research targeted at people (approval No. 192102). We had 37 children in the lower grades of elementary school enjoy the game. They evaluated the game highly, and most of them gave positive comments, such as "It's fun." They also evaluated the level of difficulty of the game as "suitable."

Fig. 9 shows the time spent by each of the 37 subjects for overcoming all of the 14 events and reaching the goal. The horizontal axis represents the time spent for reaching the goal, while the vertical axis denotes the number of game players. For example, the bar graph above 120 seconds on the horizontal axis shows the number of people who spent between 61 seconds and 120 seconds. The results at the end of the 7 events in the first half and at the end of the 7 events in the second half are shown on the graph.

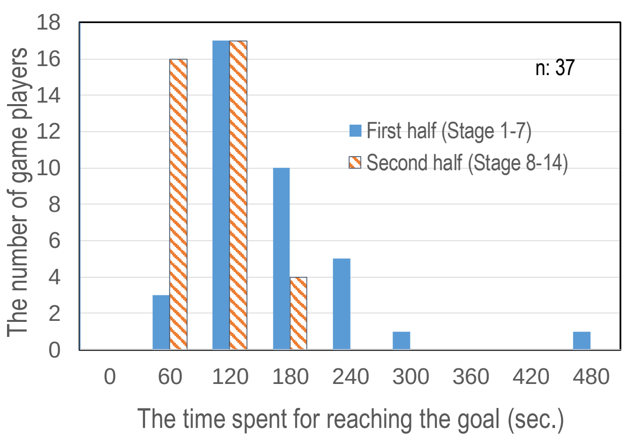


Fig. 9. The figure shows the time spent by each of the 37 subjects for overcoming all of the 14 events and reaching the goal. The horizontal axis represents the time spent for reaching the goal, while the vertical axis denotes the number of game players.

In this game, a guide is placed in each event to facilitate the player's progress in the game, in order to determine color blindness screening based on the time spent for the game alone. Color combinations of the guides are all different in consideration of differences in visibility among color-blind players. Color combinations of the guides for the 7 events in the first half were difficult for players with color blindness, while color combinations of the guides for the 7 events in the second half were easily visible. As for the 7 events in the first half, 3 players spent 60 seconds or less, 17 players spent over 60 seconds and within 120 seconds, 10 players spent over 120 seconds and within 180 seconds, and 5 players spent over 180 seconds and within 240 seconds. However, two players who spent over 240 seconds are excluded here, as there could have been troubles during the game. 86% of the 35 players completed the first half of the game within 180 seconds. In the 7 events in the second half, 16 players spent 60 seconds or less (including the two players who spent over 240 seconds in the 7 events in the first half), 17 players spent over 60 seconds and within 120 seconds, and 4 players spent over 120 seconds and within 180 seconds. Excluding the two players who spent over 240 seconds in the 7 events in the first half, 89% of the 35 players completed the second half of the game within 120 seconds. The time spent by players for the 7 events in the second half is 60 seconds shorter than the time spent for the 7 events in the first half. The factors behind this difference are considered to be "visibility of the guide" and "familiarity with the game operation." For normal color vision people, the visibility of both the guide that appears in the first half and the guide that appears in the second half is good. Therefore, it is considered that the 60-second reduction was mainly because they got accustomed to the game operation.

In Fig. 9, we further study the 4 players who spent over 120 seconds and within 180 seconds for the 7 events in the second half. 2 out of the 4 players here spent more time for the 7 events in the second half than for the 7 events in the first half. For color-blind people, the guides that appear in the first half would be less visible and they would spend more time for the 7 events in the first half than for the 7 events in the second half, but this was not the case for these two players. The two players seemed to have lost concentration during the 7 events in the second half, which caused them to spend more time for the 7 events in the second half than for the 7 events in the first half. Finally, we examine the remaining two players. These two players spent 224 seconds and 237 seconds, respectively, for the 7 events in the first half, and 141 seconds and 154 seconds, respectively, for the 7 events in the second half. Both of them reduced the spent time by about 80 seconds for the 7 events in the second half. Considering that more than 80% of the players were able to reduce the time spent for the 7 events in the second half by about 60 seconds as they got accustomed to the game operation as mentioned above, it can be predicted that "20 seconds," which is "80 seconds by these 2 players" minus "60 seconds as a result of getting accustomed to the game operation," is the time associated with the visibility of the guide for these two players. Color combinations of the guides for the 7 events in the second half are easily visible to people with color blindness. However, not all of the guides for the 7 events in the second half are easily visible for all color-blind people due to individual differences in visibility. Hence, the cumulative time spent for perceiving each guide in the 7 events in the second half is likely to be reflected in these 20 seconds. Therefore, these two players may be color blind, and should be recommend to undergo a formal color vision screening test. It is said that there is one color-blind person in every 20 Japanese males, and we believe that the results of this preliminary screening of two possibly-colorblind persons among these 37 children are within the acceptable range. In summary, although the number of subjects cannot be said to be sufficient, the guiding function in the action game proposed in this paper can be used for the preliminary screening of color-blind people.

V. Conclusion

Apps for testing color vision have been already distributed in the market, but they are intended for "checking whether a subject has color weakness," and lack entertainment. Those who are not interested in color vision deficiency tend to avoid the use of such apps. In this study, we aim to develop a digital learning game that can be enjoyed by anyone from the viewpoint of Color Universal Design and motivate players to undergo a color vision test if color weakness is suspected.

At present, color vision screening for Japanese school children is not conducted unless their guardians request, so it is necessary to educate guardians about color weakness. At a scientific event targeted at citizens, we had children play the game described in this paper after obtaining their guardians' consent. We expect that this will contribute to the early detection of color weakness among children and the deepening of guardians' understanding of color vision variation.

Any of elementary, middle, and high schools in Japan does not provide opportunities to actively learn about color blindness, and, as described in this paper, parental understanding and consent are necessary for screening for color blindness. In Japan, generations with no experience of color blindness screening tests will reach the age of parents of elementary school students around the 2030s. At that time, education to promote the understanding of color blindness will be even more important than it is at present, and the progress of this study will be of higher significance. We plan to continue to exhibit at science-related events for the general public to contribute to the early detection of children with color blindness and to promote understanding of color blindness among their guardians.

One possible limitation of this study is that it is difficult to proceed with testing the practicality of the digital learning game we have developed in Japan due to human rights concerns. The most effective solution is to get cooperation from a large number of color-blind people. However, there are only a small number of people in Japan who disclose their color blindness, and it is difficult to find color-blind people in general. Naturally, it is also difficult to gain cooperation in the field of school education. Therefore, we believe that the practicality of this digital learning game can be verified by making the game available online for a large number of users and confirming the emergence of the "tendency related to the delay caused by the visibility of the guide" between the "distribution of people with normal color vision with respect to the time spent" and the "distribution of color-blind people with respect to the time spent," as shown in Fig. 9 of this paper.

"Set of color combinations recommended by Color Universal Design" suggests "color combinations that are relatively easy to distinguish," "color combinations that are difficult to distinguish," and "color combinations that are somewhat difficult to distinguish." From now on, we would like to study the instant visibility for "color combinations that are somewhat difficult to distinguish" by utilizing this action game.

Appendix

To experience the action games in Section IV of this paper, please visit the following URL, http://kanazawa.p-product.net/game/ .

Acknowledgment

During the course of this study, we received valuable information regarding the application development and prior work from Mr. Tsubasa Takeda and Ms. Misa Tanaka. We express our deep gratitude. We would like to thank the former Associate Professor Sumio Nakamura of Kanazawa Institute of Technology and Professor Toshiyuki Yamamoto of Kansai University for their advice when writing this paper.

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