BlueVR: Design and Evaluation of a Virtual Reality Serious Game for Promoting Understanding towards People with Color Vision Deficiency

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People with color vision deficiency (CVD) often encounter color-related challenges in their daily life, which are difficult for those with non-CVD to comprehend fully. Therefore, we designed a Virtual Reality (VR) serious game, *BlueVR*, to simulate challenging scenarios encountered by people with CVD and facilitate understanding from people with non-CVD. We conducted an empirical study with thirty participants with non-CVD and six participants with CVD to evaluate the opportunities and challenges of *BlueVR*. Our findings suggest that *BlueVR* increased people with non-CVD's understanding, awareness, and perspective-taking abilities towards people with CVD. Moreover, interviews with participants with CVD revealed that *BlueVR* accurately depicts their real-life discomforts and meets their expectations to improve potential social awareness. This research contributes valuable insights into the mechanisms underlying the effectiveness of VR serious games in promoting understanding and design implications for future game development.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; • **Applied computing** → *Computer games.*

Additional Key Words and Phrases: Color Vision Deficiency, Empathy, Serious Game, Virtual Reality

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1 INTRODUCTION

Color vision deficiency (CVD) is a common genetic condition that affects how people perceive and distinguish colors [42]. People with CVD may have difficulty differentiating between specific

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colors, perceiving only two primary colors, or mixing the three primary colors differently than people with non-CVD [44]. As color plays a crucial role in various aspects of life, people with CVD face challenges and discomforts in selecting outfits, identifying cooked meat, and adjusting screen colors [48].

CVD affects up to 8% of males and 0.5% of females [35, 43]. Despite its prevalence, many people have a limited understanding of CVD [8]. Misconceptions include the belief that all people with CVD experience the same severity level and cannot perform daily tasks such as recognizing traffic light states. The social stigma associated with color vision deficiencies not only affects people with CVD emotionally (e.g., children with CVD may experience a slower learning process due to difficulties in following instructions [3, 17]), but also impacts their career opportunities (e.g., certain professions require full-color perception, such as pilots and designers).

One possible cause of these misunderstandings is that people with non-CVD lack a direct and embodied experience of viewing the world from an impaired color vision. Despite the availability of introductory articles and simulated images that depict impaired color vision, it remains challenging to imagine the lived experience of people with CVD. Researchers have developed various simulation tools to simulate the CVD experience, including web extensions [36], mobile applications [18], and Virtual Reality (VR) systems [1, 23, 55]. The primary goal of these simulation tools is to assist designers in creating inclusive designs [37]. However, there is a broader need to foster understanding and empathy among people with non-CVD toward those with CVD. For example, educators are encouraged to enhance their comprehension of the challenges faced by people with CVD and provide appropriate support to students with CVD [5].

Previous research has explored the use of VR applications and games to simulate impaired color vision for people with non-CVD [1, 13, 23, 33, 55] since VR can provide powerful immersive and embodied experiences. These VR applications employed various strategies, such as visual simulation, color-based tasks, and gamification. For example, Ahn et al. [1] designed a VR experience based on tasks that simulated the challenging experience of CVD, where participants were required to match red or green screws with the corresponding holes on a board. Their findings indicated that VR efficiently promoted self-other merging, attitude, and helping behavior toward people with CVD. Jones and Ometto [23] developed a generalized model for simulating impaired color vision. Wang et al. [55] used gamification strategies and developed an embodied VR game that simulated a bartender scenario, utilizing color-based tasks to raise awareness about CVD. Despite the potential benefits of VR and gamification in improving understanding and empathy, more comprehensive studies are needed to examine the underlying mechanisms. This gap may stem from insufficient evaluation and limited exploration. Furthermore, research is scarce on the perspectives of people with CVD towards scenario and task simulation.

Therefore, this paper aims to investigate how to design VR simulation games that enable people with non-CVD to embody the perspectives of people with CVD. More specifically, our research questions (RQs) are as follows:

- RQ1: What are people with CVD's experiences and challenges living with CVD? And how to present their living experiences through a VR simulation game?
- RQ2: Can a VR simulation game facilitate the understanding and empathy of people with non-CVD toward people with CVD?

To answer RQ1, we first recruited six participants with CVD and conducted semi-structured interviews to gain insight into their color-related experiences and daily challenges. With insights from this interview, we designed *BlueVR*, a VR game that allows players to take the perspective and experience the daily life of people with red-green deficiency, a most common form of CVD [35]. To reflect on the promises and challenges of *BlueVR* in facilitating understanding and empathy

(RQ2), we further evaluated *BlueVR* with 30 participants with non-CVD. Also, we asked Study 1 participants with CVD opinions about the final game.

Our findings suggested that *BlueVR* promotes players' understanding of CVD in the way people with CVD expected based on an analysis of the results of Study 1 and 2. Specifically, participants in Study 2 with non-CVD reported that *BlueVR* expanded their initially narrow understanding of CVD, enabling them to propose helpful solutions. This outcome aligns with the expectations expressed by individuals with CVD in Study 1. Furthermore, our research highlighted the advantages of using VR simulation and inclusive game design to foster empathy and understanding and provided design implications for future VR empathy games. Our contributions include (1) *BlueVR*, a VR game that simulates the daily challenges of CVD to increase understanding and facilitate empathy toward people with CVD; and (2) empirical evidence of the underlying mechanisms of VR and gamification that could inform the design of future VR empathy games.

2 BACKGROUND: COLOR VISION DEFICIENCY

In this section, we start with literature explaining CVD to understand this population comprehensively and then further demonstrate their daily challenges and social stigma.

2.1 Understanding Color Vision Deficiency

Human beings perceive the visible spectrum of colors through three types of eye cones: long wavelength (L), middle wavelength (M), and short wavelength (S) [42]. Color vision deficiency (CVD) is a reduced ability to perceive specific wavelengths of visible light [34]. The causes of CVD can be genetics [42], age-related macular degeneration, exposure to chemicals or drugs, eye injuries, or diseases like glaucoma or cataracts [53]. CVD is classified based on the cones that are affected. Protan refers to a deficiency in the L cones, Deutan corresponds to similar conditions with the M cones, and Tritan is associated with similar conditions with the S cones [44]. Protan and Deutan deficiencies lead to difficulties perceiving red-green colors, while Tritan deficiency affects the perception of yellow-blue colors. Another taxonomy for CVD is based on the colors individuals can perceive. Anomalous Trichromacy abnormally mixes three primary colors (red, green, and blue). Dichromacy refers to perceiving only two primary colors, and Monochromacy is characterized by a complete absence of color discrimination [44]. The most common forms of inherited CVD are protanopia (red-green color deficiency) and deuteranopia (green color deficiency) [58].

2.2 Challenges and Social Stigma Faced by People with CVD

Color is one of the most important primary information sources, so people with CVD experience CVD-related challenges in their daily life, including the following four aspects [11]: **(1) Comparative**: to match or differentiate colors, **(2) Connotative**: to use color as a way of coding implicit meanings, **(3) Denotative**: to mark out or organize colored objects in complex visual displays, and **(4) Aesthetic**: to create an emotional response or convey a mood and also elaborated on the detailed tasks in each category that people with CVD were particularly having trouble with. Besides these physical challenges, they also experience social stigma attached to color vision deficiencies, as many people with non-CVD have a limited understanding of CVD [8]. For instance, some people mistakenly believe that CVD is simply a lack of color knowledge, leading to inappropriate suggestions or assumptions about people with CVD (e.g., HR suggested remedial art classes for an employee with CVD who cannot perform color-coded work [38]). Another common misconception is that CVD is a disability that hinders people from performing tasks requiring accurate color perception. However, most people with CVD can adapt and find alternative ways to identify and distinguish colors. These social stigmas negatively impact the mental and social well-being of individuals with CVD, affecting their social interactions and self-esteem [3, 17] and perpetuating a sense of being intellectually inferior or lazy [8]. Furthermore, these misunderstandings about people with CVD can result in social exclusion and limited job opportunities in specific career paths, such as pilots or electricians, where accurate color perception is required [9, 11].

3 RELATED WORK

In this section, we provide an overview of previous research and applications that have aimed to simulate the visual experiences of people with visual impairments. Also, we explore the role of VR and games in fostering understanding and perspective-taking skills toward minority groups.

3.1 Simulated Experiences of Visual Impairments in VR

Virtual Reality (VR) is a real-time computer-simulated 3D environment that allows audiences to interact with visual stimuli through sensorimotor inputs [7]. Researchers and designers have adopted and deployed games and VR environments to simulate different kinds of visual impairment experiences, including cataract [27, 41, 61], glaucoma [10, 61], macular degeneration [26, 61], cornea disease [26], refractive errors (myopia, hyperopia, and presbyopia) [26, 29, 41] and CVD [19, 23, 32, 41, 61]. Early work focused on re-creating realistic virtual worlds to represent the living visual experiences of people with various visual impairments through video recording and visual filters [2, 4]. For instance, Ates et al. mounted a wide-angle camera on a head-mounted display to create a see-through stereoscopic display. They simulated six different types of visual impairments by applying different filters to this head-mounted display. [4]. Similarly, Ai et al. provided a recorded tour of an apartment in a VR desktop application and simulated macular degeneration by warping the central area of the simulated environment [2]. These works mainly focused on the visual experience of wearing a head-mounted display and proved that it was a useful simulation tool for visual impairments. Later, some researchers further explored 3D-simulated games and VR environments to simulate visual impairment experiences and implemented interactive game-based tasks in [28], such as tasks related to visual perception encountered in people's daily life [47, 51]. For instance, Väyrynen et al. asked users to navigate through a virtual urban landscape in macular degeneration, cataract, myopia, and glaucoma vision and search for particular objects in VR [51]; in another work, Stock et al. simulated the effects of cataract, glaucoma, and age-related macular degeneration by implementing a Gaussian blur filter in a virtual domestic environment [47]. Although the performance of these works was not as promising and did not include user tests, they revealed the potential of VR interaction to simulate visual impairments. In our research prototype, *BlueVR*, we implemented a color-differentiating task to simulate CVD experiences, using the physiologically-based model presented by Machado et al. [33] for the simulation of protanomaly.

3.2 Empathy and Its Developmental Models

Generally, empathy has been viewed as the process whereby one person tries to understand another person's subjectivity accurately and without prejudice [57]. Although researchers in varied fields hold varied definitions of empathy, they have taken two primary approaches to study it: the cognitive empathy approach and the affective empathy approach. In the former, empathy is a process of understanding another person's perspective [16], which is used interchangeably with "perspective taking" [22]. Affective empathy focuses on the observers' emotional responses to (and understandings) other people's affective states [39]. Recently, other researchers have proposed the physical aspect of empathy, referring to the sensations and understandings facilitated through physical simulations [16, 60]. Thus, this work aims to facilitate cognitive and physical understanding and affective empathy towards individuals with CVD among people with non-CVD.

Moreover, research has shown that empathy and helping behavior can be promoted with prosocial digital media and computer-mediated communications, such as social media, video games, and VR applications, and that empathy can be developed through processes [24, 31, 56]. For instance, Watson and Greenberg [56] concluded three steps of the empathy development process: emotional simulation, perspective-taking, and emotion regulation; whereas Keskin et al. later proposed a more detailed seven-stage process: acting, meaning, imagination, perspective-taking, and feeling [24]. Based on their processes, López-Faican and Jaen [31] presented an adapted circular model of empathy specifically for designing interactive systems and playful experiences—observing, meaning, imagination, perspective-taking, feeling, understanding, and acting. In this research, we adopted the acting process in our game to raise participants' awareness of people with CVD.

3.3 VR and Games for Enhancing Understanding and Empathy towards Minority Groups

Researchers designed various video games and VR applications to provide living experiences to facilitate understanding and empathy toward minority groups, such as children [40], chronic pain patients [50], refugees [59], psychosis [20], and homeless people [22]. Furthermore, findings from their studies have shown that video games and VR applications are helpful vehicles for fostering understanding of and empathy (perspective-taking) toward vulnerable populations through narrative storytelling and plots [59], interactive tasks with multi-modal feedback (about physical limitations), role-play, and embodied avatars [50]. For instance, Twilight Rohingya demonstrated a day of a refugee boy's life through narrative storytelling in 360-degree VR video and facilitated users understanding and awareness of refugees' living conditions and difficulties [59]. In another example, AS IF embodied users into a chronic pain patient's VR avatar, allowing them to role-play a patient's tasks while experiencing physical motion limitation and resolving game puzzles [50]. Their findings showed both improved perspective-taking and emotional empathy. While a few attempts have been made to help people with CVD [1, 55], these research studies did not evaluate the empathetic outcomes. In addition, researchers have pointed out that using simulators to "be like" people with accessibility needs cannot take the place of "being with" them in the design process [6, 49]. Therefore, including minority groups' feedback towards empathy games and VR applications can avoid over-exaggerated game challenges or over-simplified tasks, allowing users/players to maintain a proper and correct stereotype and understanding of their situations. In our study, we conduct an empirical study to gather feedback from people with non-CVD and people with CVD. We validated the opportunities and challenges of utilizing embodied and interactive game tasks to facilitate understanding and empathy toward people with CVD.

3.4 Our Contributions Compared to Existing Literature

In conclusion, our research aimed to promote understanding and empathy towards individuals with CVD through VR games, filling a critical gap in the limited research on simulating the lived experience of this population. While previous researchers have explored how to display the real-life experience of people with CVD vividly [13, 37, 58], they often overlooked the involvement of individuals with CVD in the design process and the incorporation of their feedback [6, 49]. By actively incorporating the perspectives and feedback of individuals with CVD, we addressed this gap and brought their voices to the forefront of VR-simulating game design. We designed *BlueVR* based on our study findings and previous research and conducted empirical studies to evaluate the understanding and empathic outcomes. This evaluation filled the blank space of lacking evaluation in empathy-directed CVD simulative work [1, 55]. We uncovered underlying mechanisms of using VR simulation to facilitate understanding and empathy and proposed design considerations for future VR-simulating games towards CVD. We offer valuable insights and guidance to researchers and designers in developing more effective VR-simulating games.

4 STUDY 1. INTERVIEWING PEOPLE WITH CVD

Our study consisted of three steps. First, we conducted interviews with six participants with CVD to gain insights into their experiences related to the condition (Study 1). Based on the findings of Study 1, we developed the VR game – *BlueVR*. Finally, we conducted an empirical study with participants with non-CVD to evaluate the game and collected feedback from participants with CVD by conducting interviews (Study 2). We present the study process in Figure 1.

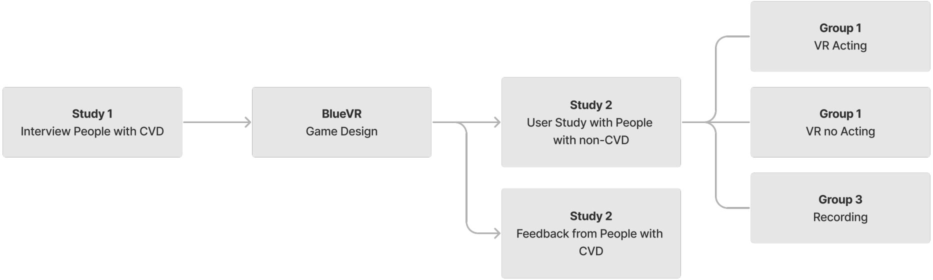

Fig. 1. Overview of the study stages and process.

We conducted an interview study with 6 participants who have CVD to investigate their lived experiences and challenges related to color-related issues. The primary goal of this study was to gain a better understanding of the emotional and social impacts caused by CVD conditions. By gathering insights from their experiences, we aimed to enhance our understanding of living with CVD and better design empathy-directed game tasks. The Institutional Review Board of Duke Kunshan University approved the study design.

4.1 Participants

We recruited six participants with CVD via WeChat Subscription. The participants were five males and one female, ages 20 to 26 (M=22.8, SD=2.56). Individuals had to be diagnosed with CVD and have experienced color-related challenges to be eligible for participation. Five participants reported a red-green deficiency, while the other (P3) had a blue-yellow deficiency. All participants (n=6) were unaware of their condition until diagnosed during a physical examination, and none had prior knowledge about the classification of CVD or the specific cones affected. After the interview, participants received a 50-dollar compensation in local currency. Appendix A has more detailed demographic information about the participants.

4.2 Procedures

In our study, we used convenience sampling to recruit participants who self-reported having CVD. To assess their eligibility for the study, we used an online Ishihara color test on ColorMax® [12] as a screening survey to confirm their CVD types. We invited participants who met the eligibility criteria to participate in a 30-minute semi-structured interview.

We provided all participants with a clear explanation of the study's purpose, voluntary participation, and the requirement for audio recording. Confidentiality and anonymity of their responses were assured. All participants provided electronic consent before participating in the study. After signing the consent form, we asked participants to complete an online survey collecting their demographic information, including age, gender, education level, CVD types, and experiences of color-related challenges. Then, we invited them to a 30-minute semi-structured interview via VooV Meeting[1], an online conferencing software. We designed the interview questions to explore their experiences of color-related challenges and the potential social and emotional impacts. Appendix B has the interview questions. We recorded the interviews for later data analysis using the embedded recording function of Tencent Meeting.

4.3 Data Analysis

The interviews were audio-recorded with participants' consent and later transcribed into text. Two co-authors conducted a thematic analysis on the transcripts, where both authors read the transcripts to gain a sense of the data and then developed a set of initial codes independently. They then discussed their initial codebooks and reached an agreement. The emerged common themes included 'experiences living with CVD,' 'physical impacts of CVD,' 'social impacts of CVD,' and 'participants' attitudes and solutions towards CVD.' These themes were consistent across the transcripts and provided insights into the real-life experiences of people with CVD.

4.4 Results from Study 1

4.4.1 Participants' Experiences and Challenges Living with CVD. Findings suggested that participants' experiences (N=6/6) were not identical but rather diverse on a spectrum due to varying categories and intensities of CVD. For instance, participants with red-green deficiency reported different color spectrums that were hard to differentiate. Two participants (P-cvd4, P-cvd5) reported a spectrum between yellow and green, while another (P-cvd5) reported green and blue. Additionally, most participants (N=5/6) reported that they were unaware of their CVD conditions or challenges in their daily life until they received a diagnosis or examination. After being diagnosed with CVD, they recognized some difficulties caused by their CVD conditions (N=5/6). For example, P-cvd5 reported difficulty identifying the colors of indicator lights on a charger, which meant *"a situation that can be quite uncomfortable"* to him. Most participants (N=5/6) reported a loss of confidence and emotional struggles in their ability to identify colors after being diagnosed with CVD. While their vision abilities remained unchanged, two participants (P-cvd2, P-cvd5) experienced a marked shift in confidence. For example, before diagnosis, P-cvd5 attributed their difficulties in identifying colors to special cases (e.g., confusing colors used in the design) rather than CVD. At the same time, he lost confidence in their ability to identify colors or engage in color-based conversations after diagnosis. He expressed,

> *"I didn't feel like my life was affected much after being diagnosed (with CVD), but I became very doubtful about myself......Especially when I see something that appears in yellow or green, I start to panic and feel anxious, wondering if it's either yellow, green or even if it's red or orange!"*

Most participants (N=5/6) initially thought living with CVD did not significantly affect their daily lives. However, when prompted to recall specific daily-life scenarios, they (N=5/6) mentioned several uncomfortable experiences and how they resolved them. For instance, most participants (N=5/6) mentioned a common scenario - shopping. Four participants reported difficulties in choosing colored outfits and make-up, such as selecting the right shade of lipstick. Another participant (P-cvd3) noted difficulties in buying other goods at the supermarket. Another common troublesome scenario reported by three participants (N=3/6) was identifying traffic lights, but all of them

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[1] https://voovmeeting.com/

had developed their specific way as it was a frequent and essential situation. These color-related challenges created uncomfortable and inconvenient living situations and further decreased their confidence in handling tasks that involved color perception. For instance, P-cvd1 mentioned that they felt regret after realizing that they had been *"wasting money on clothes of the wrong color"* (P-cvd1).

4.4.2 People with CVD's Solutions for Color-Related Difficulties. All participants with CVD (N=6) actively sought solutions to overcome color-related difficulties and minimize the negative impacts of CVD on their daily lives. One typical method they adopted (N=3/6) was to *"recognize"* colors through alternative channels or modalities, such as focusing on brightness levels, using visual aids like images, or relying on audio cues. It was advantageous in situations like identifying traffic lights mentioned by two participants. Another strategy is to avoid colors that are difficult to differentiate when making choices (N=3/6). For instance, P-cvd5 stated that he *"only chose highly saturated colors"* to avoid *"any transitional colors that are too moderate or low-saturation colors, which is hard to differentiate for me."* During urgent scenarios, participants (N=3/6) reported seeking assistance and help from their friends or salespeople with non-CVD to identify colors or make color-related decisions.

4.4.3 Social Stigma Faced by Participants with CVD. In addition to the challenges related to color perception and the emotional impact, participants with CVD also shared experiences of social challenges, including social stigma. Most participants (N=5/6) expressed that people with non-CVD tend to hold stereotypes about their condition, ignoring the variations in types and intensities of CVD. Some participants (N=4/6) reported that when they disclosed their CVD conditions, they were commonly questioned whether they were able to identify traffic lights or drive. Besides, most participants (N=5/6) mentioned that scenarios that required color-based communications imposed social stigma on them. For example, one participant said, *"People always egged me with curiosity on identifying the color of certain objects"* (P-cvd4). However, some participants (N=3/6) felt that by doing so, people did not necessarily mean to understand their visions but usually to *"ridicule our incompetence in identifying the color"* (P-cvd5). Such social stigmas were sometimes unintentionally induced. For instance, when the friends of one participant discussed fashion with him, involving color-based topics, he would *"feel bad"* because his friends were *"unaware of his difficulties in color-related topics and lack of confidence"* (P-cvd2).

Participants had diverged viewpoints when asked about their perceptions of the social representations of CVD. All participants (N=6) acknowledged that their CVD situations were not fully understood by people with non-CVD, leading to stereotypes, misunderstandings, and social stigma. Some participants (N=3/6) felt that their deficiencies were usually over-exaggerated, which created even more challenges for them. *"Many people doubted my competence in video editing due to my CVD, but what I had was a minor blue-yellow deficiency"* (P-cvd6). Nevertheless, most (N=5/6) indicated a sense of helplessness and a tendency to disengage from the social stigma because *"I can do nothing with social stigmas"* (P-cvd2) and felt that it was *"impossible to be understood (by people with non-CVD)"* (P-cvd4).

5 GAME DESIGN

In this section, we introduce the objectives, design principles, game mechanics, and player interactions and flow in *BlueVR*, following insights gained from Study 1.

5.1 Design Objectives

Based on the results from Study 1, we follow the below objectives when designing *BlueVR*:

- **Accurately represent the visual experiences from the perspective of people with CVD.** We used a CVD filter to provide an embodied experience, which has proven effective in invoking self-other merging in previous studies [1, 22]. We choose red-green deficiency (Protan and Dichromacy) when simulating CVD visual effects since it is the most common type [58]. To show the color spectrum, which is hard to identify for people with red-green deficiency, we use colors on the color wheel between red and green in the task design.
- **Allowing people with non-CVD to understand the living challenges of people with CVD.** This involved identifying typical scenarios and discomforts representing life with CVD and incorporating them into the game scenario. Based on the findings of Study 1, we concluded the following features should be involved in our designed scenario: 1) beyond the stereotype scenario (e.g., driving); 2) allowing color-based tasks which included various colors; 3) the information used to finish the tasks should not limit to colors. Therefore, we chose the convenience store as the typical scenario to reflect the color-related discomforts shopping scenario. To further capture the various CVD-related challenges, we designed shopping tasks following the four types of color-usage troubles (comparative, denotative, connotative, and aesthetic) identified by Cole et al. [11].

5.2 Game Mechanics and Core Design Features

5.2.1 Simulating CVD Visual Experiences through a VR Camera Filter. We used a filter volume that rendered red-green deficiency color visions on the VR camera. We adopted LMS color space to simulate the response of three types of human eye cones, following Wang et al.'s CVD VR experience [55]. Specifically, according to a prior CVD simulation research [33], we set the filter parameters in a 3×3 LMS matrix (Protanomaly LMS matrix. The matrix columns represent L, M, and S cones, while the rows represent R, G, and B intensity.). We then converted the parameters to RGB color space to simulate the red-green deficiency.

$$\begin{pmatrix} 0.152286 & 1.052583 & -0.204868 \\ 0.114503 & 0.786281 & 0.099216 \\ -0.003882 & -0.048116 & 1.051998 \end{pmatrix}$$

5.2.2 Simulating CVD Living Challenges through Puzzle-Solving Tasks. We designed the game tasks in correspondence to the four major challenges defined by Cole [11]. Players start at a crossroads and then proceed to complete tasks inside a convenience store. More specifically, players need to complete the below tasks.

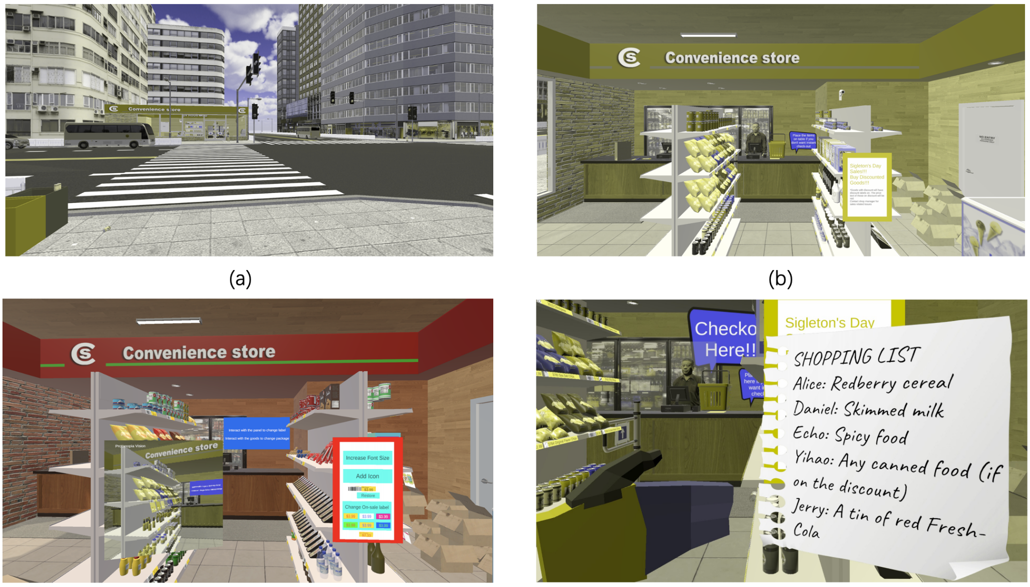
Judging the states of traffic lights. As a common color-related discomfort [46], the crossroad crossing task (Figure2.a) serves as an introductory exercise for participants to become accustomed to impaired color vision. Players needed to judge the state of a traffic light that could only be distinguished by their colors (the green color is to pass while the red color is to stop), which creates comparative difficulties [11].

Matching items to a list. The central puzzle of *BlueVR* is to match items from a list (Figure2.d) to the goods in a convenience store (Figure2.b). We designed two lists with unique CVD challenges, and each task on any list would reflect one or multiple types of CVD conditions [11]. Players needed to find the correct item out of other disturbance items, e.g., the chocolate milk out of milk cartoons of other favors. Appendix D shows all the items in the game, including the targets and disturbances.

Modifying Scene Settings. Finally, the game allows players to switch views from the CVD filter to the full-color view (Figure2.c). Then, players can conduct helping behaviors by changing the scene settings (Figure3.a) with options to:

- Change the font size of the price tags (Figure3.b).
- Add signs to the price tags describing the contents of goods (Figure3.c).
- Change the colors of the shopping item's packages (Figure3.d).
- Change the colors of on-sale labels (Figure3.e).

5.2.3 The Empathy Development Stages through Game Tasks. Our game simulates two major challenges faced by people with CVD: crossing the crossroad under traffic light control [46] and shopping in a store. In consideration of empathy as one of the anticipated outcomes of our game experience, we have integrated the seven-stage empathy development model proposed by López-Faican and Jaen [31] into three game stages: observing, perspective-taking, and acting. The three puzzle-solving tasks described in section 5.2.2 are designed based on these three stages. The first crossroad scene is employed to observe environments under impaired color vision. We designed the second matching task for the perspective-taking stage, where players can shop like individuals with CVD and experience a transfer of perspective. The third modifying task allows players to act for individuals with CVD, enabling them to modify the scene setting based on their experienced CVD-related challenges. We have also added another matching task after the *Acting stage*, which serves as a reflection, allowing players to experience how their modifications facilitate shopping. Figure 4 illustrates the entire game flow.



SHOPPING LIST
Alice: Redberry cereal
Daniel: Skimmed milk
Echo: Spicy food
Yihao: Any canned food (if on the discount)
Jerry: A tin of red Fresh-Cola

Fig. 2. Screenshots of game scenes. (a) The Cross Road. (b) The Convenience Store in CVD vision for the Shopping Challenge Stage. (c) The Convenience Store in the full-color vision for the *Acting stage*. (d) The Shopping list in Shopping Challenges.

(a) (d) (e)

Fig. 3. The toolkit for supporting people with CVD in the acting scene. (a) The world-space UI to change labels. (b) An original label. (C) A new label with font increased, and an icon added. (d) The UI to change good packages. (e) CVD lens for previewing the changes.

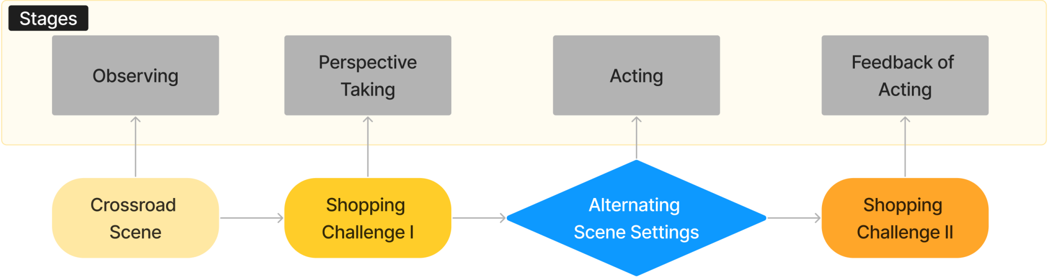


Fig. 4. The game flow of each scene and its empathy developmental stage.

5.3 Technical Implementation

We developed *BlueVR* in the Unity game engine (v2021.3.3f1). Public assets, including the buildings, the avatar, sound effects, and background music, were from Unity Asset Store and an open-source academic website [54]. BlueVR was tested on *HTC Vive Pro Eye* or *Meta Quest 2*.

6 STUDY 2. USER STUDY

To address our research question, we conducted a controlled experiment using three different versions of *BlueVR*, each offering a distinct level of interaction with the environment. Our objective was to examine the impact of the interactive elements on participants' understanding and empathy toward people with CVD. Additionally, we sought to assess whether VR's immersive and interactive nature provided unique benefits in fostering understanding and empathy compared to a more passive medium such as video.

Furthermore, to comprehensively evaluate our scenario and task design, we conducted another qualitative interview with six participants with CVD, who were the same participants in Study 1. This interview session is called a "feedback-gathering session" in our following discussions. During this session, participants were shown a recording of *BlueVR* and engaged in semi-structured interviews that lasted approximately 20 minutes. We specifically explored the participants' views on the differences between the game and real-life situations and their perspectives on our game design.

6.1 Participants

We recruited a total of 34 participants from [two anonymous universities] in China. Recruitment was done via convenience sampling, including posting an advertisement on the university's online community and personal reach out. All participants were undergraduate or graduate students aged 19-26 (mean age = 21.2). Four participants were part of a pilot study to identify any usability issue with *BlueVR*, and we excluded their data from the analysis. The final sample (N=30) consists of 11 males and 18 females, and 1 participant identified as a transgender female. Seventeen participants had experienced VR before. Among them, 16 participants had used VR less than ten times. Twelve participants had met people with CVD before, but only one participant reported being familiar with someone with CVD. Appendix A has more participants' demographics. All participants received ¥100 as compensation for completing all our study sessions. The research protocol for this experiment was reviewed and approved by the Institutional Review Board of Duke Kunshan University. Participants had the right to withdraw from the experiment at any time during the study sessions.

For the feedback-gathering session, we invited the six participants who had participated in Study 1 through email. We requested their participation in a 20-minute interview to provide feedback on our game. All six participants voluntarily agreed to participate in the feedback-gathering interviews. We compensated these participants with ¥50 for participating in this study (Study 2).

6.2 Study Design

Our experiment had a between-subjects design. The main part of the experiment is the game experience. We set three groups using three different versions of *BlueVR* to evaluate the effects of VR and the *Acting-stage*:

- **VR Acting**: *BlueVR* with all stages, including observing, perspective-taking, and acting;
- **VR no Acting**: *BlueVR* without the *Acting-stage*, with an exploration stage with a full-color vision instead;
- **Recording**: Recorded videos of the VR no Acting Group, which serve as the baseline of *BlueVR* with only game information contents.

Participants were evenly distributed to the three groups, and each participant completed the experiment individually. For the two VR groups, participants in the VR Acting Group used the *HTC Vive Pro Eye* head-mounted display (HMD), while participants in the VR no Acting Group used the *Oculus Quest 2* HMD. The HMDs were set to a single-eye resolution of 1440×1600 and a refresh rate of 90 Hz. In the Recording group, participants were provided with recorded videos of the *VR no Acting* group game-play. The video was recorded by one of the researchers and had a resolution of 1920×1080 and a frame rate of 60 frames per second (fps). The experiment consisted of three main phases: a pre-test survey, the game experience, and a post-test survey. The dependent variables are empathy level and understanding level toward people with CVD. These variables were measured using four empathy scales and a knowledge test. Before the game experience, participants completed the Interpersonal Reactivity Index (IRI) questionnaire [15], the Questionnaire for Cognitive and Affective Empathy (QCAE) [39], and the knowledge test. After the game experience, participants filled out the same questionnaires (IRI and QCAE) as in the pre-test survey, with three additional questionnaires, the Inclusion of Other in the Self (IOS) scale [21], and two adapted empathy subscales specifically focused on people with CVD.

6.3 Material

6.3.1 Empathy. We used two empathy questionnaires to evaluate the empathy outcomes. We involved the Interpersonal Reactivity Index (IRI) [15] and Questionnaire for Cognitive and Affective Empathy (QCAE) [39] in our pre-test and post-test survey. These two scales have been validated and showed reliability in English [14] and Chinese [30, 45]. Moreover, the questions in IRI and QCAE are easy to adapt to our context. Therefore, we choose IRI and QCAE to measure different dimensions of empathy, including cognitive empathy, perspective-taking, affective empathy, empathic concern, personal distress, and fantasy.

We compiled two subscales further to investigate participants' empathy towards people with CVD. One subscale adapted ten questions of IRI, and the other adapted 12 questions of QCAE. We asked participants to rate how much they empathize with people with CVD. These questions were only involved in the post-test survey.

In the post-test survey, we also used the Inclusion of the Other in the Self (IOS) scale [21]. IOS is a single-item, pictorial measure of closeness and connectedness. We asked participants to select the picture that best represents the current relationship between them and people with CVD.

6.3.2 Knowledge Test. We designed a knowledge test to evaluate whether the participants can map color in full-color vision to color in impaired color vision. The *Acting-stage* of *BlueVR* provides an asynchronous comparison of colors in two visions. We hypothesized that participants would establish a dim mapping of colors in different visions. The initial version of the knowledge test consisted of four multiple-choice questions, one heat map question, and two open-end questions. We used daily challenges, except for shopping, as the context of questions. These contexts tested if the participants could transfer the color-mapping knowledge to real life beyond the game. Then we excluded one multiple-choice question and one open-end question based on the feedback of four people with CVD. In our final knowledge test, two multiple-choice questions tested whether participants could identify the most similar color between red-green impaired color vision and full-color vision. The other multiple-choice question was about the least contrasted color pair in red-green impaired color vision. The open-end question asked the participants to describe the potential inconvenience for people with red-green CVD when cooking food. Participants with CVD provided the sample answers to the open-end question.

6.3.3 Willingness to Help. We designed three self-reported questions to measure participants' willingness to understand and help people with CVD. Participants were asked to rate how well the sentences described them from 1 (Not at all) to 10 (Extremely willing).

6.3.4 Feedback-Gathering Interview Guideline. The interview was conducted with the specific goals of 1) gathering participants' opinions on our game, 2) understanding any discrepancies between the game scenarios and their real-life experiences with CVD, and 3) receiving their suggestions and recommendations for improving the game. For example, one of the questions asked participants, "What are your likes and dislikes about this game, and why?" The complete list of interview questions can be found in Appendix B.

6.4 Study Procedure

We included three sessions in the experiments. The detailed information of all sessions is shown in Figure 5.

Consent and Pre-test Survey. Participants were provided with a consent form and the link to the pre-test survey via messaging one day before the experiment. After giving consent, participants filled out the pre-test survey on the Qualtrics online questionnaire system. The pre-test survey

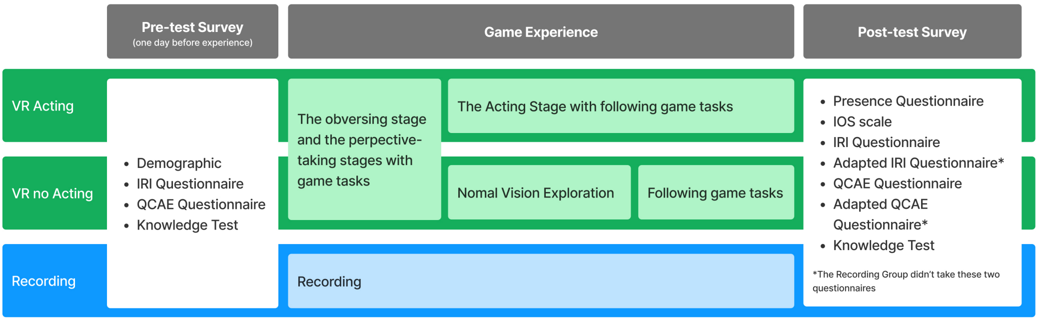


Fig. 5. The study procedures.

collected participants' demographic information and their trait levels of empathy by IRI and QCAE scales.

Game Experience. For participants who were assigned to the two VR groups, the researchers guided them to wear the VR headset, which would be *HTC Vive Pro Eye* or *Meta Quest 2*, depending on their group. Before the game experience, all participants underwent a calibration process to adjust the HMD in different viewing angles until their vision was not blurred. Then, we asked them to do some basic interactions, such as moving, turning around, grabbing, and activating the shopping list. They were allowed to practice freely. The *BlueVR* game experience started when participants confirmed familiarity with the VR environment and manipulation. Participants were informed of their CVD type (red-green deficiency) in VR conditions. They proceeded to engage with the game flow, which involved completing a shopping task, either observing or taking action in a full-color vision, and subsequently completing another shopping task. To mitigate potential biases resulting from differences in task difficulty, we presented the two shopping tasks in random order. In the control condition (Recording), participants received a brief introduction to CVD and *BlueVR* before watching the recording through a laptop.

Post-Test Survey. After finishing the Game Experience session, participants were asked to take the post-test survey on the Qualtrics system. They reported their sense of empathy, understanding, and awareness through related scales and questionnaires. All the experimental sessions took, on average, 60 minutes to complete.

Feedback-Gathering Interview. We conducted the interview separately from the previous sessions. Before the interviews, the participants signed a consent form. Next, we showed them the same video as in the Recording group. After viewing the video, we conducted a 20-minute semi-structured interview following the interview guideline. We used the embedded recording function of VooV Meeting to record the interviews for further data analysis.

6.5 Data Analysis

We analyzed the results of questionnaires, task performance, and the feedback from open-ended questions to investigate how the three versions of *BlueVR* influenced participants' empathy, understanding, and awareness towards people with CVD and their general feelings towards this experience. The Shapiro-Wilk tests showed that the dependent variables in each group were normally distributed. Mauchly's Test of Sphericity indicated that the assumption of sphericity was met for the repeated-measured dependent variables. Therefore, we performed Two-way Repeated Measures Analysis of Variance (ANOVA) for variables measured in both pre-test and post-test and

One-way ANOVA for variables measured only in the post-test. For the open-ended questions and feedback-gathering interviews, we used the open-coding approach [25] to analyze the responses and transcripts. Two authors coded the data through an inductive approach and independently extracted themes. The authors then reviewed the data and discussed the themes to determine the final results.

7 RESULTS

7.1 Quantitative Findings: Knowledge Test, Willingness to Help, and Empathy Scales

Figure 6 presents each group's mean knowledge test scores in the pre-test and post-test. Before experiencing *BlueVR*, the VR no Acting Group had the lowest average knowledge test score ($M = 2.03, SD = 0.87$) compared to the Recording Group ($M = 2.33, SD = 1.23$) and VR Acting Group ($M = 2.33, SD = 0.89$). However, after the game experience, the average knowledge test score of the VR no Acting Group became the highest ($M = 2.77, SD = 0.64$) compared to the Recording Group ($M = 2.62, SD = 0.82$) and VR Acting Group ($M = 2.50, SD = 0.78$). All groups' average and median values of the knowledge test score variation (before and after the study) were positive. A Two-way Repeated Measures ANOVA was conducted on the knowledge test scores to investigate these findings further. The results indicated that there was no significant interaction effect of *Time (pre-test / post-test)* and *Group* on participants' knowledge test results ($F(2, 27) = 0.68, p > .05, \eta_p^2 = 0.05$). Moreover, no significant main effect of either *Time* ($F(1, 27) = 3.57, p > .05, \eta_p^2 = 0.12$) or *Group* ($F(2, 27) = 0.03, p > .05, \eta_p^2 = 0.003$) was observed. Given that the knowledge test specifically evaluates the ability to map colors between full-color vision and impaired color vision, the results imply that *BlueVR* was ineffective in improving participants' color-mapping knowledge. However, the responses to open-ended questions in the questionnaires revealed that *BlueVR* has the potential to promote other forms of knowledge related to CVD, which we further discuss in Section 7.2.

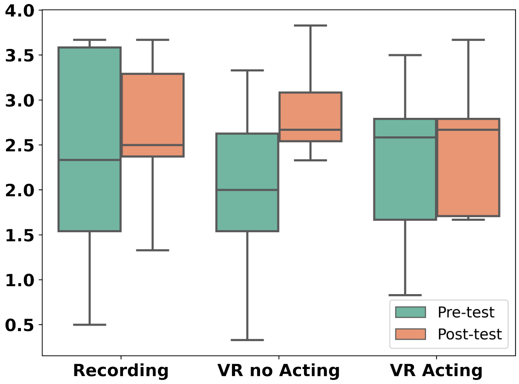


Fig. 6. Mean knowledge test score in pre-test and post-test of each group.

We conducted a one-way ANOVA to analyze participants' self-reported willingness-to-help ratings, collected only in the post-test. Figure 7 displays the results. The Recording Group ($M = 26.10, SD = 3.07$) had a higher average willingness-to-help score compared to the VR no Acting Group ($M = 24.20, SD = 4.10$) and VR Acting Group ($M = 23.80, SD = 4.96$). However, no significant differences were found among these three groups($F(2, 27) = 0.89, p > .05, \eta_p^2 = 0.06$). The statistical analysis did not indicate that the *Acting-stage* in *BlueVR* significantly impacted participants' willingness to help people with CVD. We explore other potential factors contributing to this result in Section 8.1.

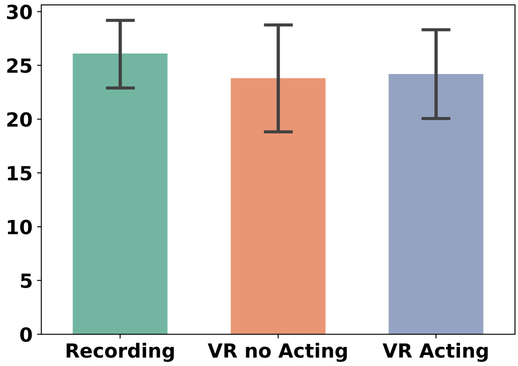


Fig. 7. Mean willingness-to-help ratings of each group. Error bars indicate standard deviations.

We conducted a Two-way Repeated Measures ANOVA to analyze the IRI and QCAE empathy results (Figure 8). For either scale, we did not observe a significant interaction effect between *Time* and *Group*, IRI: $F(2,27) = 1.00, p > .05, \eta_p^2 = 0.07$; QCAE: cognitive empathy subscale: $F2,27) = 2.67, p > .05, \eta_p^2 = 0.17$; affective empathy subscale: $F(2,27) = 0.68, p > .05, \eta_p^2 = 0.07$. Additionally, we did not find a significant main effect of *Time* and *Group* on these empathy subscales. The lack of significance may be attributed to the high initial level of empathy observed across all groups, making it challenging to detect significant statistical changes in our study.

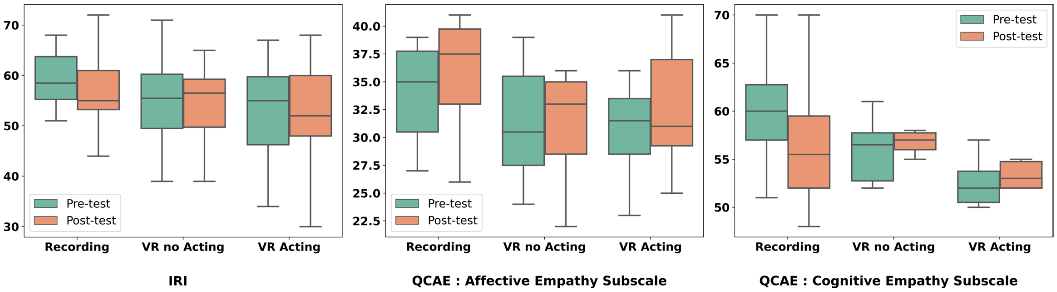


Fig. 8. Results of each empathy scale in pre-test and post-test of each group.

7.2 Qualitative Findings: Understanding and Awareness of People without CVD

From the qualitative results of the open-end survey questions, all participants (N=30/30) reported feeling immersed in *BlueVR*'s CVD visual effects and understood people with CVD better. Nine participants indicated that the yellowish environment was their most impressive feature in *BlueVR*. For instance, three participants reported feeling shocked by the great discrepancies between the impaired color vision displayed in VR and what they physically experience in full-color vision. Another three participants (P-nv1, P-nv10, P-nv22) reflected that they began to realize that red-green deficiency ”is not just limited to red and green” (P-nv10), which provided a more comprehensive understanding of people with CVD. Another participant also (P-nv30) indicated that ”the

CVD-related challenges are far more difficult than what I used to think, (even include) simply 'distinguishing the colors of traffic lights.'" Especially when asked, "What kinds of solutions do you think can help people with CVD?" seven participants in the VR Acting group mentioned enlarging fonts, which was reported to be one of the most helpful solutions from participants with CVD in the feedback-gathering session. In contrast, only two participants in the VR no Acting group and one in the Recording group mentioned enlarging fonts. The difference indicated that participants in the VR Acting group established a deeper understanding of CVD.

Providing alternative information was proposed in the answers of all three groups, including improving colors (N=10/30) and adding symbols/figures (N=4/30), which participants with CVD also mentioned. Besides, participants proposed some novel solutions beyond what we provided in *BlueVR*'s *Acting-stage*, including designing packages according to the shape of products (P-nv22), providing special shopping guidebooks for people with CVD (P-nv26), and categorizing goods with labels (P-nv4, P-nv34).

Participants also showed a better awareness of CVD-related challenges. Upon analyzing the text of the answers, we observed more positive and engaged attitudes in the two VR groups compared to the Recording group. Participants in the two VR groups used more specific and positive descriptions when asked about their feelings toward CVD-related challenges. They described the challenges to be *time-consuming* (VR Acting Group: N=2/10, VR no Acting Group: N=2/10), *need more information* (VR Acting Group: N=1/10, VR no Acting Group: N=4/10), and *can be solved by design* (VR Acting Group: N=2/10, VR no Acting Group: N=3/10). While in the Recording Group, 6 of 10 participants regarded the CVD-related challenges as *difficulties* and *hard work*. Furthermore, there was a difference in how participants expressed their awareness of assisting people with CVD. In our last question, "Did you feel having more understanding of color vision deficiency (CVD)? Can you talk more about your findings of CVD?" four participants in the Recording group emphasized the need for further societal support, compared to 2 participants (P-nv5, P-nv6) in the VR Acting Group and none in the VR no Acting group.

While participants generally exhibited improved understanding and heightened awareness regarding CVD, it is essential to note that certain instances of over-exaggeration and expressions of sympathy and pity were observed. Specifically, a small number of participants (N=4/30) explicitly expressed pity towards individuals with red-green deficiency. Additionally, a subset of participants (N=4/30) used negative terminology such as "suffering" (P-nv33) and "monotonous" (P-nv7) when describing the impaired color vision. Furthermore, some participants (N=11/30) used adverbs of degree with strong and excessive connotations when characterizing the severity of difficulties faced by those with CVD. This result may be attributed to the shift between full-color vision and impaired color vision. In the real world, most people with CVD have congenitally impaired color vision, lack a point of reference for full-color vision, and become accustomed to their impaired color vision. However, in *BlueVR*, players' vision shifts from their full-color vision to an unfamiliar impaired color vision, The contrasts in physical vision may elicit a significant sense of discomfort.

7.3 Qualitative Evaluations from People with CVD

In order to gather feedback on *BlueVR*, we invited the same group of people with CVD (5 with red-green deficiency and 1 with yellow-blue deficiency) who had previously participated in Study 1 to the feedback-gathering interview. We presented them with a recording of the complete gameplay (including the *Acting-stage*) and interviewed them about the game's contents. They provided positive reviews of *BlueVR*, highlighting its ability to simulate the CVD challenges moderately. They also recognized the benefits of utilizing VR technology and praised the inclusion of the novel *Acting-stage*, showcasing our game's inclusivity. Additionally, they offered valuable suggestions and some new design ideas for future game iterations, focusing on enhancing the inclusive design and overall gaming experience of *BlueVR*.

7.3.1 Moderately Simulated CVD Experience. During the evaluation of the simulated CVD experience in *BlueVR*, participants were asked to provide feedback on their general impressions of the game, as well as more specific aspects such as the color vision simulation, challenge design, and other aesthetic elements. Regarding their general impressions, all participants (N=6/6) provided positive feedback on how *BlueVR* effectively simulated CVD and related challenges. One participant praised *BlueVR*'s game flow, which ”guides player naturally from crossroad to shopping challenge” (P-cvd6). However, he also mentioned that other aspects of guidance in *BlueVR* seemed weak, such as instructions within the convenience store, because they were ”largely limited to text descriptions,..., not very intuitive to players” (P-cvd6).

For the color vision simulation, all participants with red-green deficiency (N=5/6) confirmed that the simulated color vision in *BlueVR* was moderate. Three of them (P-cvd1, P-cvd4, P-cvd6) stated that they did not perceive a difference in color vision, indicating that the color vision simulated in *BlueVR* was almost identical to theirs. Other participants (P-cvd2, P-cvd5) thought that the simulated CVD was slightly more intense because ”the color in *BlueVR* seemed to be darker than what I perceive” (P-cvd2). The diverged intensity of CVD echoed the results of study 1. However, these two participants did not express concerns about the over-exaggeration of CVD symptoms. One of them (P-cvd5) thought that the exaggeration of CVD in *BlueVR* was moderate and could even be recognized as a practical approach to convey CVD-related difficulties.

For the task design, four participants agreed that the shopping challenges in *BlueVR* moderately reflected their real-life shopping experiences. For instance, one participant with red-green deficiency mentioned his ”sufferings to differentiate colors like yellowish green or orange” (P-cvd5) when shopping, which was on the spectrum between red and green. One participant noted that the challenge was well reflected in *BlueVR* since the colors of goods packages were intentionally chosen from the hard-to-differentiate spectrum (P-cvd1). Another participant mentioned relying on textual information on goods packages to identify them (P-cvd6), a strategy many players with non-CVD adopted in *BlueVR*.

Still, participants mentioned some nuances that needed to be included in *BlueVR*'s future task design. On the one hand, as two participants would argue, time limitation was a significant challenge that *BlueVR* did not mention (P-cvd4, P-cvd5). ”In fact, you may just stay 10 to 15 seconds in front of the shelf with chips, and then decide on one for tonight's snacks” (P-cvd4) instead of spending several minutes finding the correct good on a shopping list. On the other hand, one participant thought that the lack of social interactions rendered the shopping experience at *BlueVR* harder than her own experience (P-cvd6). She always asked salespersons or strangers without CVD for help whenever she needed help identifying goods' colors, which was not an option for players to choose in *BlueVR* (P-cvd6). However, the same participant also recognized the value of the crossroad challenge, which incorporated social category interactions by assigning an animated female avatar to provide hints on when to cross the road. This approach aligned with her strategy in similar scenarios (P-cvd6).

7.3.2 VR as an Effective Media for Demonstrating CVD. When evaluating VR as the medium for demonstrating CVD, most participants (N=5/6) agreed that VR was effective. Some participants (N=3/6) recognized that the immersive nature of VR ”allowed players to be free from disruptions caused by their color vision, enabling them to focus more on experiencing the perspective of people with CVD as portrayed in the VR headset.” (P-cvd6). Participants emphasized that the high information density and the sense of embodiment in VR significantly contributed to the practical demonstration of CVD. ”Compared to textual or 2D graphical demonstrations, VR provided a more intuitive and information-rich experience by directly engaging players in the perspective of CVD." one participant explained (P-cvd6). Another participant commented that in *BlueVR*, "When wearing the VR headset in *BlueVR*, the player virtually became one of us" (P-cvd2). They also believed such embodiment could "potentially raise the player's level of empathy toward people with CVD" (P-cvd2).

7.3.3 *Acting-Stage as a Physically and Emotionally Effective Strategy for People with CVD.*

The *Acting-stage* in *BlueVR* received positive feedback from our participants. All (N=6/6) agreed that the design options provided in the *Acting-stage* effectively addressed the physical challenges people with CVD face in shopping scenarios. Participants were impressed by the ability to modify the color of goods' packages in this stage, as it "allowed players to develop their unique strategies for differentiating goods and reduced the likelihood of confusion"(P-cvd1).

Some participants (N=3/6) found that modifying texts or icons was the most effective strategy in the *Acting-stage*, not only because "text is the most reliable information source" (P-cvd4) but also due to "the long-term lack of confidence in our perception of colors" (P-cvd5).

Interestingly, one participant (P-cvd2) noted that the *Acting-stage* could provide emotional support for people with CVD. Although *BlueVR* was initially designed for players with non-CVD, this participant felt that the *Acting-stage* could "give me the confidence to start playing this game" (P-cvd2). He indicated that he felt heart-warming by how the game mechanics in this stage allowed him to modify package colors, which enabled him to "differentiate goods without wearing CVD correction lens"(P-cvd2).

Participants also believed that the *Acting-stage*, in general, could foster empathy among people with non-CVD toward people with CVD (N=4/6). "By experiencing the challenges of modifying goods' colors or price tags from the CVD perspective, they understood how to avoid creating color-related difficulties for people with CVD" (P-cvd1). Another participant also commented that "if the retailers played it (*BlueVR*) before, they would never have manufactured or sold so many goods with disgustingly indistinguishable colors!" (P-cvd4).

7.3.4 *Expectations on More Diverse and Inclusive Game Design.*

For future improvements of *BlueVR*, participants expressed a desire for diversity in the simulation of CVD, including different types of CVD on the spectrum and varying intensities. One participant suggested including blue-yellow deficiencies and Achromatopsia, the partial or total loss of color vision (P-cvd3). Another participant mentioned that players should be able to adjust the intensity of CVD because "for people with CVD, each color vision can be unique" (P-cvd5). One participant further proposed including a color vision test at the beginning of *BlueVR* because "I want *BlueVR* to simulate my color vision precisely so that my friends could better understand my vision through this game"(P-cvd2). Additionally, two participants (P-cvd2, P-cvd6) suggested implementing a "virtual color correction lens" feature in *BlueVR*. One of them thought such a feature could "help people with non-CVD understand how well we can differentiate color with such lens" (P-cvd6).

To conclude, participants with CVD not only expected *BlueVR* to have diversity but also the ability to address every specific color vision of them, including the cases they wear color correction lenses, in the simulation of CVD.

Besides the diversity in simulation, participants suggested that *BlueVR* could increase its inclusion by including people with CVD as target audiences. They showed interest in other aspects of the game beyond the *Acting-stage*. One participant regarded shopping tasks with in-time feedback as "good training for my daily shopping scenarios" (P-cvd2). They believed that *BlueVR* could potentially prepare him ready for real-life shopping scenarios without "suffering the economic loss of buying the wrong goods" (P-cvd2). Another participant appreciated "the overall enjoyment and fun of experiencing a real-life simulation game in *BlueVR*" (P-cvd6).

Regarding the feedback mechanism, participants emphasized the need for more inclusion in *BlueVR*, especially for future players with CVD. They mentioned that when playing video games, ”players with CVD had a completely different mindset with players with non-CVD” (P-cvd2). While they acknowledged that the current feedback system is ”precise and in-time” (P-cvd2), some participants (N=3/6) expressed concern about the potential negativity and criticism implied in the feedback messages. ”Your family members were disappointed about you” might be interpreted as ”a criticism or irony towards people with CVD” (P-cvd3). They suggested a more inclusive approach that ”positively encourages players to amend their mistakes” (P-cvd2). While agreeing that feedback should honestly tell players where they did wrong, one participant argued that for players with CVD, such feedback should ”appear only at the end of the game” (P-cvd2) because the timely feedback during the gameplay may ”reduce the already low confidence level of players with CVD in continuing this game” (P-cvd2).

8 DISCUSSION

In this research, we introduced the design process and iterations of a VR game, titled *BlueVR*, based on the interview result of Study 1. We then conducted Study 2 to evaluate this game's effectiveness in facilitating the general public's understanding and empathy toward people with CVD. We also investigated whether increasing the level of interaction (i.e., providing action opportunities to alter the scenes) in *BlueVR* would lead to a greater sense of understanding and empathy.

We aimed to answer RQ1 by interviewing six participants with CVD in Study 1 to gain insights into their CVD-related daily struggles. Interview findings revealed three necessary key features to accurately represent their experiences: 1) scenarios that go beyond common stereotypes, 2) color-based tasks that incorporate a variety of colors, and 3) inclusion of information beyond colors necessary to address CVD-related challenges. Following these insights and design features, we implemented *BlueVR*, a VR game where players could engage in color-related shopping tasks in a convenience store. Subsequently, we conducted Study 2 to answer RQ2. Findings from Study 2 showed that *BlueVR* effectively improved people with non-CVD's understanding toward people with CVD. However, the lack of significant statistical results indicated that *BlueVR* did not improve people's empathy towards people with CVD, which was contrary to our initial expectations. Next, we discuss the promises and challenges of using a VR simulation game like *BlueVR* to facilitate players' understanding and empathy towards people with CVD.

8.1 Challenges and Promises on Promoting Understanding towards People with CVD through a VR Simulation Game

Despite the lack of significant statistical differences in the knowledge test results, participants provided highly positive feedback in the post-test survey, reporting an increase in their understanding of CVD. Therefore, the lack of statistical significance in the knowledge test results could possibly be caused by the content of the questions because the multiple-choice questions mainly tested participants' ability to map color perceptions of full-color vision to impaired color version (see knowledge test question in Appendix E). Such insignificant findings indicated that participants could not accurately map colors from full-color vision to impaired color vision, instead of their empathetic attitudes or understandings. This result may be attributed to the task-directed game flow of our game design, where participants focus more on completing tasks using non-color information, such as text and graphics, rather than identifying similar colors and mapping them to a full-color vision. In contrast, participants provided highly positive feedback in the post-test survey, which findings revealed an increased understanding of CVD and suggested a positive response to RQ2. Specifically, participants' answers to the post-test open questions in Study 2 aligned with CVD participants' interview feedback from Study 1. This alignment included an improved understanding of confusing color ranges beyond red and green, challenging scenarios beyond traffic lights, and the significance of non-color information. Such results indicated that *BlueVR* successfully improved players' understanding of CVD, bringing it closer to the expected social awareness of people with CVD. Moreover, according to qualitative feedback from Study 2, *BlueVR* allows players to experience a realistic and visualized impaired color perspective, which corrects potential misconceptions about CVD (e.g., red-green color blindness only affects the distinction between red and green) and increases players' awareness of the importance of non-color information. Therefore, our designed immersive VR experience and increased level of interaction in *BlueVR* improves the understanding of CVD among people with non-CVD to a certain extent.

We did not observe any significant differences in the empathy scales comparing participants' self-reported ratings before and after Study 2, which provided a negative answer to RQ2. This result may be attributed to the limitations of the empathy scales used in our study. We employed IRI and QCAE for pre-test and post-test comparisons. However, these scales are primarily designed to assess long-term empathy traits, which may not be easily influenced by a 20-minute game experience. Future research should investigate and develop more appropriate measures to evaluate the empathetic outcomes of empathy-directed works.

The lack of significant differences in empathy and willingness-to-help also prompted us to reconsider how VR works to facilitate empathy. The study result of Ahn et al.'s prior work [1] proved the positive effect of embodied vision compared to instructing to imagine CVD from the full-color vision. They suggested that embodied VR experience has a positive effect on enhancing self-other merging, attitude, and helping behavior toward people with CVD. In our study, we investigated the effect of VR (compared with 2D screen) and user engagement strategy (Acting or not). However, we received a contradictory result compared to Ahn et al. [1]. This result was unexpected, as previous research reported that VR and game-based strategies effectively enhanced perspective-taking and empathy [20, 22, 52]. One potential explanation for the inconsistent result between our study and Ahn et al.'s could be that the primary factor driving the effect in an embodied VR experience is the embodiment of impaired color vision rather than the immersive nature of VR. As mentioned by some participants in our study, the visual simulation of CVD was the most influential factor in *BlueVR*. While VR technology does provide a more immersive visual experience, its impact on improving the empathetic outcomes of our game may not be significant. Besides, a potential explanation for the limited effectiveness of VR and game-based strategies in our study context could be attributed to the difference in the implemented perspective-taking mechanism. In previous empathy-directed VR works, participants take another person's perspective through a designed narrative flow, including changing scenarios, events, and tasks [52]. This gradual accumulation of understanding facilitated empathy in the target groups' experiences. However, in our game, players experienced impaired color vision directly through visual feedback (the CVD filters), with subsequent tasks and narratives to experience color-related scenarios and the impacts of CVD in daily life. Therefore, *BlueVR* players' perspective-taking and understanding were facilitated by direct physical and visual sensations instead of narrative or embodied avatar aspects. This mechanism of perspective-taking may have directed players' focus towards accommodating impaired color vision rather than empathizing with the experience of CVD-related challenges. As mentioned by some participants, the initial impressions of CVD primarily focused on the yellowish color tone, indicating a potential distraction from our intended focus on considering how impaired color vision affects the daily lives of people with CVD.

While the statistical results did not support the effectiveness of the *Acting-stage* in improving empathy and knowledge acquisition, the qualitative result suggested that the *Acting-stage* could effectively facilitate a deep understanding of people with CVD. From the answers to open-end questions, participants in the VR Acting Group were able to recognize the importance of non-color information when confronting CVD-related challenges. Additionally, the positive interview feedback received from participants with CVD implies the potential value of this strategy; Participants with CVD perceived that the *Acting-stage* could improve people's understanding and awareness of CVD. In particular, one participant with CVD highlighted that the *Acting-stage* not only had the potential to enhance empathy among people with non-CVD but also could boost the confidence of people with CVD. The participant noted that the *Acting-stage* provided an opportunity to create and experience a user-friendly shopping environment, which is often not easily accessible in real life for people with CVD. These findings all suggest the promising points of the design features in *BlueVR* and positive answers to RQ2. However, future research could further investigate the potential of the *Acting-stage* in improving knowledge acquisition and empathy among individuals without CVD, as well as promoting the confidence of individuals with CVD.

8.2 Potential Factors on Eliciting Unintended Pity

While most participants emphasized the importance of non-color information, a few of them also expressed sympathy and pity towards people with CVD. Here, pity refers to sharing sadness as a negative aspect of sympathy [24], whereas empathy involves the attempt of one self-aware self to understand the subjective experiences of others. The sympathetic outcomes that the participants with non-CVD felt towards individuals with CVD were unintended. One potential factor is that participants with non-CVD compared impaired color vision with full-color vision, whereas people with CVD do not experience full-color vision. This comparison may lead participants with non-CVD to develop unnecessary pity associated with impaired color vision. Furthermore, people with CVD are more sensitive to the brightness of colors since they have to be continually exposed to similar colors and need to identify confusing colors in everyday situations. Although players experienced the same vision towards people with CVD in *BlueVR*, their ability to identify similar colors differed significantly from that of people with CVD. *BlueVR* players' inability to adapt to impaired color vision and differentiate similar colors intensified their discomfort, leading to a distressing impression of CVD-related challenges and evoking feelings of sympathy. Although sympathy and pity might emerge as byproducts during the empathy development process [24], we recommend that future research consider approaches to minimizing sympathy when designing empathy development.

Another potential reason for participants' sympathy feelings could be the inattentive leading narrative in *BlueVR*. We employed a narrative to convey their performance outcomes in each stage, intending to engage players and help them comprehend the potential embarrassment caused by CVD. However, the negative description of potential outcomes may have heightened the discomfort associated with having CVD. Future research could explore the use of narratives in a more objective manner, avoiding emotion-leading descriptions that indicate what would be felt by the avatar.

8.3 Design Considerations for VR Simulation Games to Facilitate Empathy

Based on the results from both studies, we identified key design insights for future VR-simulation games like *BlueVR*, which be addressed in future work to create a more effective and engaging experience that promotes understanding and empathy towards people with CVD.

Simulate real-life scenarios of people with CVD beyond visual filters. One of the most important features to simulate the CVD condition in VR is the visual representations of CVD's physical impairments, as investigated in this work and previous research [1, 55]. The qualitative feedback from Study 2 demonstrated that incorporating everyday scenarios and color-related tasks improved players' understanding of CVD-related challenges. Meanwhile, participants with CVD also proposed some dynamic factors to consider in other potential situations, e.g., time limitation or emergent situations, as well as social interactions with non-playable characters (NPC) to increase the realism and variety of daily situations they have faced. Thus, players would be able to further learn about people with CVD's challenges through embodied experiences beyond visual filters and simulations.

Simulate diverse types and intensities of CVD conditions. One of *BlueVR*'s limitations stemmed from its fixed CVD type and intensity based on qualitative feedback from participants with CVD. Participants with CVD expressed their desire to demonstrate an adjustable simulation that could accurately reflect the diversity of CVD. Considering the effectiveness of *BlueVR*'s CVD simulation in improving understanding, diverse CVD simulations can further expand players' understandings of CVD, addressing the stereotypes reported in Study 1. Providing a more nuanced and accurate representation of CVD conditions in VR through visuals or narratives would help present individualized CVD situations, thereby facilitating a better understanding of the unique experiences of particular individuals (e.g., family members and friends).

Involve players' own perspectives and provide opportunities for action. The implementation of *Acting-stage* in *BlueVR* received participants' positive feedback with non-CVD and CVD. Unlike traditional empathy-driven VR experiences that solely enable users to experience the perspective of targeted groups, *BlueVR* allowed players to switch to their own perspective and take action to create a CVD-friendly environment after experiencing the perspective of people with CVD. In our game, we introduced an isolated session for taking action, where players were provided with control panels and CVD-simulated glasses to improve the environment. This feature enabled participants with non-CVD to test various approaches to enhance the shopping experience. By gaining firsthand experience and understanding the potential impact of each improvement, the *Acting-stage* facilitated a better understanding of how different types of information contribute to the process of gathering and interpreting information. While these features were effective to improve the environment, the interaction itself had limitations in terms of flexibility and natural integration with real-life simulations. Future work can explore different types of interactions and introduce other types of challenges/solutions to players, further enhancing their understanding of CVD conditions.

Design inclusive experiences towards people with CVD. Participants with CVD valued the inclusive design that enables *BlueVR* to be accessible to them. According to their feedback, the *Acting-stage*, which allowed players to create a CVD-friendly environment, mitigated the sense of inferiority arising from their inability to identify colors accurately. This result underscored the potential of VR simulation games to create value beyond facilitating understanding and empathy. We suggest that future VR simulation games should consider incorporating inclusive features for players with CVD, such as incorporating embedded tools to compensate for CVD. Additionally, designers should consider crafting different narratives tailored to players with and without CVD. Furthermore, we suggest that general applications consider incorporating CVD-friendly features. Taking into account the unintended benefit observed in *BlueVR* for people with CVD, making applications accessible to people with CVD may greatly benefit them.

8.4 Limitations

Our work has several limitations. Firstly, three co-authors conducted the three experimental groups in Study 2 independently at different research sites. Due to variations across sites, we were unable to achieve a balanced demographic representation in terms of participants' gender within each group. This may introduce uncertainty in the interpretation of the results. Besides, the limited diversity of our participant pool, consisting solely of university students, raises concerns about the generalizability of the study results to a broader population of players. Second, since the proficiency of VR manipulation varies among participants, there might be different perceptions regarding the task difficulty levels. Some participants perceived the tasks as easy to handle, while others reported them as hard to complete. Finally, the sample size of our work is relatively small for a between-group study, which made it difficult to detect the significance levels in the statistical tests. Future work can recruit a larger group of participants to analyze further the impact of the VR game on players' empathy levels and knowledge gains.

9 CONCLUSION

In this paper, we present *BlueVR*, a VR game aimed to facilitate people's understanding and empathy towards people with CVD. The game was designed based on insights gathered from interviews conducted with six participants with CVD. Our design goal is to illustrate the world from the perspective of people with CVD and present their daily challenges. We conducted an empirical study on 30 participants with non-CVD to evaluate the effectiveness of our game. The results of our study suggest that *BlueVR* has the potential to improve the understanding, awareness, and perspective-taking abilities of people with non-CVD towards people with CVD. In addition, interviews with CVD participants reveal that *BlueVR* accurately depicts their real-life discomforts and meets their expectations for potentially improving social awareness. These findings underscore the potential of VR-simulating games as a powerful tool for promoting understanding and awareness towards people with CVD and other different forms of disabilities or challenges.

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A PARTICIPANTS DEMOGRAPHICS OF STUDY 1 AND STUDY 2

Table 1. Demographics of Participants with CVD

Number	Age	Gender	Types of CVD	Diagnosed time and situation
P-cvd1	26	Male	Red-green color blindness	Driving License medical checkup
P-cvd2	22	Male	Red-green color blindness	College annual medical checkup
P-cvd3	20	Female	Red-green color blindness	High school medical checkup
P-cvd4	25	Male	Red-green color blindness	Primary School medical checkup
P-cvd5	24	Male	Red-green color blindness	Higher Education Entrance Exam medical checkup
P-cvd6	20	Male	Blue-yellow color blindness	Higher Education Entrance Exam medical checkup

Table 2. Demographics of Participants with non-CVD

VR Acting			VR no Acting			Recording		
Number	Age	Sex	Number	Age	Sex	Number	Age	Sex
P-nv1*	20	Female	P-nv12*	20	Male	P-nv24*	23	Female
P-nv2	19	Female	P-nv13*	21	Male	P-nv25	26	Female
P-nv3	18	Female	P-nv14	20	Male	P-nv26	21	Others
P-nv4	20	Female	P-nv15	21	Male	P-nv27	26	Female
P-nv5	22	Female	P-nv16	20	Male	P-nv28	23	Female
P-nv6	20	Female	P-nv17	20	Female	P-nv29	21	Female
P-nv7	20	Female	P-nv18	19	Male	P-nv30	23	Female
P-nv8	22	Female	P-nv19	20	Female	P-nv31	24	Female
P-nv9	19	Male	P-nv20	20	Male	P-nv32	23	Female
P-nv10	21	Female	P-nv21	20	Male	P-nv33	23	Male
P-nv11	19	Female	P-nv22	22	Female	P-nv34	25	Male
			P-nv23	22	Male			

*Pilot test participants.

B INTERVIEW QUESTIONS FOR STUDY 1

1. When did you first discover that you have color vision deficiency?
2. Have you ever had any trouble or challenges because of color vision deficiency in daily life and work? Can you give one or two examples?
3. Have you ever had any trouble in your interactions with others because of your color vision deficiency? Can you give an example?
4. Are you willing to actively disclose your CVD situation to people you have a relationship with?
5. Could you please tell me which industry you work in and if you have ever experienced any limitations or challenges related to color vision deficiency in your work?
6. How do you explain to people that you have color vision deficiency?
7. What's your opinion on how the general public understands color vision deficiency?

C INTERVIEW QUESTIONS FOR PARTICIPANTS WITH CVD IN STUDY 2

1. How do you feel about the game? Any thoughts? Any questions?
2. What do you like or dislike about this game? Why or why not?

(3) To summarize the game content, players were required to select the correct items based on shopping lists. How similar is that to your real-life shopping experience? Please briefly explain the similarities and differences.
   a. Do you think the difficulties in the game are more extreme or not realistic enough compared to the ones you face in your daily life?
(4) We also involve an acting part, where users can modify the scene settings to provide a colorblind-friendly shopping experience (e.g., changing the tag's text size, color, etc.). How do you feel about this part?
(5) How does this way facilitate the public's empathetic attitudes towards CVD people compared to traditional text or video? What are the pros and cons?
(6) Do you have any suggestions on how we could make our VR game more accurate to the real-life difficulties of colorblind people?
(7) Any other thoughts about how we can improve the game, or, in general, how we can deliver the idea and facilitate the public's empathetic attitudes?

D DETAILS OF CHALLENGES: MATCHING ITEMS TO A LIST

Challenge I: Cereals *(Red-berry, Candlelit, Cacao)*, Chips *(Honey Flavor, Chilli Pepper Flavor, Sea Salt Flavor, Original Flavor, Grilled Meat Flavor)*, Drinks *(Classic Beer, Premium Beer, Beer, Red Tin Cola, Blue Tin Cola, Bottle Cola, Coffee, Mineral Water, Orange Juice (Box), Orange Juice (Bottle), Cherry Licor, Wine, Champagne)*, Milks *(High-Calcium, Skimmed, Chocolate Flavored)*, Canned Food *(Meatball (On Discount), Tuna, Tomatoes Soup, Chickpeas, Organic Food)*, MISC *(Milk Chocolate with Almonds, Chocolate, Chocolate with less cocoa, Cookies, Chocolate Cookies, Sandwich with Salmon + Cucumber, Puffs)*

Challenge II: Sauces and Dressing *(Mustard, Mayonnaise, Thousands Island, Soy Sauce, Ketchup, Hot'N Spicy, Peanut Butter)*, Sandwich *(Salmon + Cucumber, Tomato + Cucumber, Ham + Lettuce, Chicken + Tomato, Tomato + Avocado)*, Canned Food *(Meatball (On Discount), Tuna, Tomatoes Soup, Chickpeas, Organic Food), Milk (High-Calcium, Chocolate, Strawberry)*, Chocolate *(Milk Chocolate with Almonds, Chocolate, Chocolate with less cocoa)*, MISC *(Classic Beer, Premium Beer, Beer, Red Tin Cola, Blue Tin Cola, Bottle Cola, Coffee, Mineral Water, Orange Juice (Box), Orange Juice (Bottle), Cherry Licor, Wine, Champagne)*

E KNOWLEDGE TEST QUESTION

(1) Which of the following colors, seen through the eyes of a protanopia colorblind person, is closest to the perception of a normal vision person? (See Figure 9)

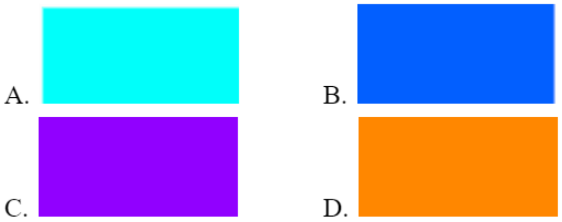
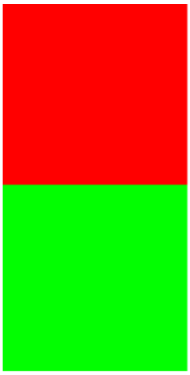
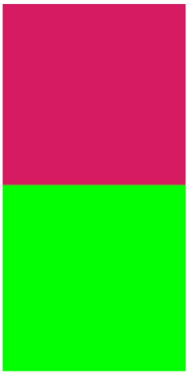
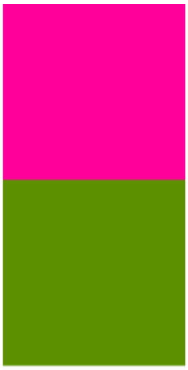


Fig. 9. Answer choices for question 1.

(2) Which of the following color pairs seen through the eyes of a protanopia colorblind person is the least contrasting? (See Figure 10)

A.


B.


C.


D.

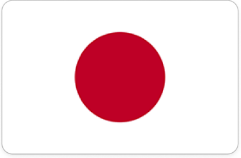

Fig. 10. Answer choices for question 2.

(3) Which of the following flags, seen through the eyes of a protanopia colorblind person, is closest to the perception of a normal vision person? (See Figure 11)

A. Argentina

B. Brazil

C. Germany



D. Japan

Fig. 11. Answer choices for question 3.

(4) Describe the potential hazards in the following diagram (See Figure 12)

Fig. 12. Diagram shown in question 4.

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