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A pilot study investigating how individuals with varying sensory characteristics perform in virtual reality environments

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Abstract

Diversity in visual perception, particularly due to age and color vision types, has been widely studied in fields such as cognitive psychology and human-computer interaction. Variations in color perception, such as those arising from dichromatic or trichromatic vision, can significantly influence object-finding tasks and overall performance in virtual environments. Recent studies suggest that while Virtual Reality (VR) environments can be designed with universal accessibility, understanding how individuals process visual cues in these environments remains underexplored.

This study investigates how individuals with diverse visual perception perform object-finding tasks in a VR environment. As part of a pilot study, participants completed tasks in two types of VR environments: one rendered in full color and the other in grayscale. The aim was to explore how different visual settings might support future research involving a more diverse participant group. While preliminary results indicated better performance in the color environment across participants, the primary focus was to assess the suitability of the experimental design and environment setup for investigating sensory interactions in VR.

By understanding how visual differences affect performance, designers can create more inclusive virtual spaces for uses like education, gaming, and training. This interdisciplinary approach, combining elements of psychology, sensory studies, and technology design, suggests a more inclusive framework for addressing diversity in VR environments. By systematically analyzing visual perception, the study not only advances academic understanding but also provides a practical roadmap for implementing inclusive VR solutions across industries.

Keywords: *Virtual reality, Visual perception, Diversity, Individual differences, Color vision*

Introduction

Visual perception is inherently diverse due to significant individual differences in how people experience and interpret color. These differences arise from variability at all levels of the color vision system, including genetic variations, environmental influences, and perceptual mechanisms. As a result, individuals inhabit unique perceptual worlds, where even seemingly objective properties like color are experienced subjectively and uniquely by each observer. This diversity highlights the complexity of human visual perception and challenges the assumption that all individuals perceive the world identically [1].

Although some studies (See [2,3]) discuss accessibility (e.g., older adults and contrast sensitivity), specific environmental attributes (e.g., contrast, luminance, depth cues) that optimize performance for diverse groups in VR are not identified. In a recent study [4], there appears to be a shift in accessibility research towards accommodating diverse bodies and minds rather than "normalizing" disabled individuals. The study emphasizes the importance of incorporating accessibility into mainstream technologies rather than relying solely on specialized assistive technologies.

Although traditional approaches like 2D displays can reproduce identical stimuli, virtual reality environments provide a more engaging and authentic experience. This immersive nature enables users to interact with sensory data in a way that closely resembles real-world experiences. By creating realistic settings with precise control over visual and spatial elements, VR paves the way for inclusive design that better addresses the varied needs and capabilities of users.

This study aims to explore how individuals with varying sensory abilities perform in a VR environment. Specifically, how does the presence of color versus black-and-white (BW) environments in virtual reality affect the performance of individuals in object-finding tasks?

This study employed a VR object finding task as a controlled environment to address this question. Participants navigated a virtual world where objects with different visual attributes were placed in diverse environmental conditions. Understanding how sensory abilities influence object-finding tasks in VR can guide the development of multimodal systems that are inclusive to all users.

By observing individual differences while in the same virtual situation, the findings of this study offer insight into designing inclusive VR experiences that cater to a broad spectrum of sensory needs. The results contribute to the fields of educational psychology and human-computer interaction, providing actionable guidance for designers in creating more accessible and effective tools for diverse user groups.

The remainder of this paper is organized as follows. First, a review of the relevant literature is presented, focusing on visual perception diversity and its implications for VR design, with particular attention to color perception and object-finding tasks. This is followed by a description of the pilot experiment, including the research design, participants, data collection, and analysis procedures. The subsequent section reports the experimental results, which are then discussed in relation to inclusive VR design and directions for future research. Finally, the paper concludes by summarizing the key findings and their broader significance.

Literature review

This literature review aims to synthesize research on the impact of color perception diversity on object-finding tasks in VR environments. By integrating findings from psychology, vision science, and VR design, this review seeks to identify current knowledge gaps and provide insights for designing more inclusive and effective virtual environments.

Visual Perception Diversity

Diversity in human visual perception is affected by different factors, such as early sensory experiences, brain development, and the ability to process both individual and group-level information. Deepening our understanding of these diverse traits is necessary for developing better ways to restore lost senses and improving Human-computer interaction in various situations [5,6].

People with varying visual senses would react differently to the same task, even simulating a different visual perception situation for the same person would result in a different response. Siong et al. [7] examined object recognition and scene categorization in young adults with normal vision under simulated low vision conditions, Participants were divided into mild and moderate simulated low vision groups. Tasks included annotating objects of interest in photos, labeling the annotated objects, and reporting the theme of scenes. Overall performance in object recognition, annotation, and scene perception significantly deteriorated with simulated visual impairment, showing that the simulated situation significantly had a negative impact on performances in object recognition, object annotation, and scene perception among participants. This indicates that visual and sensory impairments adversely affect task performance in recognizing and categorizing real-world scenes [7].

Visual acuity is essential in precision tasks; it indicates the ability to discern fine details. Variations in acuity can impact performance significantly, specifically in tasks that require high levels of detail recognition which is influenced by factors like optical image formation and retinal excitation [8]. This emphasizes how fundamental visual acuity is to task success overall and suggests that any reduction in acuity, whether due to natural variation or external conditions, could hinder performance and limit effective interaction with complex visual environments.

Research conducted by Mateus et al. [9] suggests that visual perception declines with age, High-level functions (e.g. perceiving the shape of a rotating 3D sphere based on motion) had a quadratic decline, while the decline of low-level functions (e.g. detecting the brightness of a grating or distinguishing red from green) showed a rather linear pattern, especially in spatial contrast sensitivity [9]. Furthermore, Shao et al. [2] found that age-related changes in visual perception can affect how individuals interact with data visualizations. In particular, reduced contrast sensitivity, especially at higher spatial frequencies, may make it more difficult for older adults to perceive fine visual details on screens. Therefore, to make visualizations more accessible for older viewers, increasing contrast or lowering spatial frequency is useful [2].

Seeing in 3D (stereoscopic vision) helps us understand space better by giving us depth information, which makes it easier to grasp how things are arranged and moving around us [10]. This ability is important for various everyday tasks, including reaching, grasping, and navigation [11]. When people have trouble seeing in 3D (impaired stereopsis), they feel less movement (vection) and a weaker sense of being present in virtual environments, making navigation harder [12]. However, when people with overall good 3D vision actively move their heads while viewing, they experience stronger sensations of movement compared to just passively looking [12].

Dichromats and trichromats exhibit different object recognition capabilities; Snodderly et al. [13] investigate how differences in color vision among Neotropical primates, specifically dichromats and trichromats, affect their ability to distinguish fruits from leaves in their environment. By modeling visual performance using machine learning, it explores how luminance and color contribute to foraging success in these primates. Trichromats can distinguish fruits from leaf tops with 91-96% accuracy, while dichromats achieve 59-73%. Incorporating luminance improves dichromats' performance, narrowing the gap in foraging discrimination.

While studies explore the impact of diverse visual capabilities (e.g., dichromats vs. trichromats, low vision simulation) in real-world tasks, there is limited research on how these differences play out in VR environments, particularly in object-finding tasks. Real-world tasks often provide naturalistic cues and contextual information that may not translate directly to virtual environments, where visual stimuli can be stylized, exaggerated, or simplified. Despite the increasing adoption of VR for applications ranging from training simulations to entertainment, there has been little research focusing on how variations in visual perception affect object-finding tasks in these settings.

According to Finlayson et al. [14] visual search performance in 3D space is influenced by several factors: 3D display volume, distance in depth, number of depth planes, and relative target position in depth. This study found that larger display volumes and more depth planes reduce search efficiency, while smaller volumes and targets positioned at the front of the display lead to faster responses. The relative depth of a target is more important than its distance from the starting point, and the effects of 3D display parameters go beyond those seen in 2D displays. These findings indicate how 3D spatial factors influence attention [14]. However, Finalyson et al.'s findings do not address whether the results could also apply to VR environments.

Visual Perception Differences in Virtual Reality

A study shows that by recreating familiar environments for cognitive assessments, VR can enhance ecological validity. It can capture user inputs and exploration patterns, and provides unique insights into their attention and spatial skills that traditional methods cannot obtain [15].

VR can elicit realistic behavioral and psychophysiological responses, which helps raise ecological validity in psychological experiments. Kisker et al.'s study [16] supports VR as a valuable tool for investigating real-life behavior in controlled experimental contexts. This study used VR to explore how virtual height impacts behavior, emotions, and physiological responses. Participants navigating a high virtual environment were more cautious when walking, with elevated heart rates, and a stronger sense of presence, especially those with higher trait anxiety. It can be concluded from Kisker et al. [16] findings that VR elicits lifelike emotional and physical reactions; Immersive VR environments with 3D vision, 360° view, and head tracking contribute to realistic perceptions and responses.

Additionally, Jubran et al. [17], explored the use of VR for experimental psychology by comparing participants' performance on three classical tasks in both VR and desktop environments, ensuring consistent visual and response conditions. Results showed that VR could replicate key behavioral patterns of traditional setups, with some limitations in technical precision. The results indicate VR has potential as a viable research tool, offering greater ecological validity while maintaining experimental control over experimental factors such as luminance, visual angles, and ergonomic validity of response devices, especially in naturalistic settings like a virtual classroom [17]. Existing VR studies often generalize findings across participants, overlooking how diverse visual perceptions influence behaviors like object-finding or navigation.

VR is increasingly being applied in education, especially for immersive and authentic distance or offline learning experiences. There is a study that examines how immersive virtual reality (IVR) classrooms can enhance education by mimicking traditional classroom settings while offering authentic social interactions. Key design factors, such as seating arrangement, avatar visualization, and peer presence, influence student learning, motivation, and engagement [18].

Methodology

This study investigated the impact of visual conditions on object-finding tasks in VR environments. Controlled experimental settings were used to compare performance under colored and black-and-white (BW) conditions.

1. Research Design

This study took an experimental approach to observe how different environmental conditions (color, monochromaticity, lighting, background, and depth) affect participants' ability to locate objects in VR. According to previous studies, VR provides a controlled experimental environment while allowing real-world emotional and physical reactions [15–17]. To determine whether the experimental design is effective in assessing differences in object-finding task performance between color and BW VR environments, a preliminary experiment was conducted.

Participants were asked to sit at a desk and wear a VIVE Pro Eye (HTC) head-mounted display (HMD) to engage in a VR object-finding game. The game was set up using Unity engine in a room with various lighting. We set up two environments, "first floor" and "second floor", each one with a color mode and the other with a monochrome mode. We used Unity's default "grayscale image effect" to create the monochrome mode from the color mode.

Figure 1. Order of presented conditions to each group

There were 8 lizards hidden in each environment. Colors for each lizard was assigned randomly. Participants were informed that the objects they were looking for would be lizards, but no visual representation of the lizards was shown.
To minimize the risk of cyber sickness, the experiment was conducted with participants seated. Participants could not walk or move in the VR environment; the only valid motions were turning head to the left-right and up and down.

Participants were informed that they needed to find all objects and they could complete the tasks without time limitation. There was no break between moving from environment number 1 to environment number 2. In order to make sure the sequence of presenting color/monochromaticity did not affect the results, participants were divided into two groups of four. Environment number 1 in color mode was presented to the first group first, then environment number 2 was displayed in monochrome mode, while with the second group, environment number 1 in monochrome mode was presented first and then environment number 2 in color.

The total experimental session, including informed consent, task explanation, the main VR game, and the feedback, did not exceed 30 minutes with any of the participants, although it was adjusted for individual pacing.

2. Participants

Total 8 participants were Kyushu University students (6 females, 2 males) with normal trichromatic color vision type.

3. Data description

This section outlines the type of data collected during the experiment. The gameplay of participants was recorded for 17 minutes and 29 seconds to determine the time taken to clear each level and to identify how long it took them to locate each object. The collected data were stored and protected following Kyushu University's research ethics guidelines.

4. Data Analysis

In this study, a quantitative analytical approach was used to evaluate participants' performance in a VR environment. To analyze the data, paired t-tests were used to compare the average time participants took to locate eight target objects between the color and BW conditions within each environment. In addition, one-tailed paired t-tests were used to explore potential interaction effects between visual condition and environment by analyzing performance across the two different VR settings. Prior to conducting these tests, assumption checks were performed using the Shapiro–Wilk test, which confirmed that the data were normally distributed ($p > 0.05$). This approach enabled the assessment of the impact of visual conditions on both object-finding accuracy and efficiency across the two environments.

Results

It took participants the average time of 0:48 minutes to find all objects in environment 1 under color condition and 2:27 minutes in BW conditioned environment 2. Also, it took participants 0:45 minutes to find all objects in environment 2 under color condition, and 6:20 minutes in BW environment 1 to find all objects.

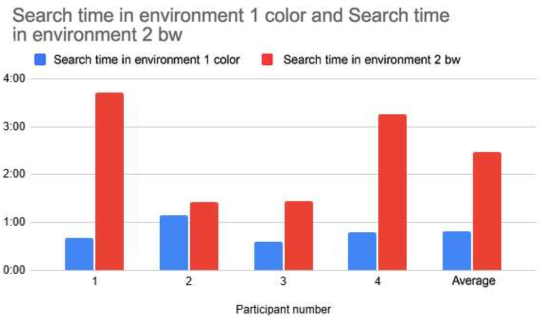

Figure 2. Search time in Environment 1 (Color) vs. Environment 2 (Black-and-White) for group 1 (Participants 1–4)

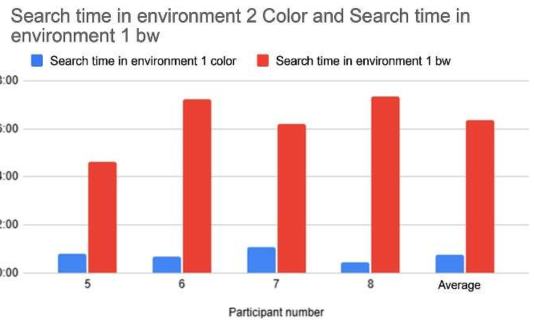

Figure 3. Search time in Environment 2 (Color) vs. Environment 1 (Black-and-White) for group 2 (Participants 5–8)

These figures compare the average time taken by participants to locate all target objects in color and black-and-white (BW) environments. The x-axis represents participant numbers, while the y-axis shows the search time (in minutes).

In both figures, a consistent trend is observed: participants spent more time locating objects in black-and-white environments compared to color environments. The data followed a normal distribution, as confirmed by the Shapiro-Wilk test ($p > 0.05$).

Table 1. Paired samples t-test comparing overall duration per second in color versus black-and-white environments (*n* = 8)

Paired Samples T-Test

Paired Samples T-Test

Measure 1		Measure 2	t	df	p
color duration	-	bw duration	−4.176	7	0.004

Note. Student's t-test.

A paired samples t-test was conducted to compare the duration participants spent in color versus black-and-white (BW) environments . Four participants experienced the chromatic environment first, while the other four began with the BW environment, allowing control for order effects. The analysis revealed a significant difference between the two conditions, with participants spending significantly more time in color environments ($M = \bar{x}_1$, $SD = s_1$) than in BW environments ($M = \bar{x}_2$, $SD = s_2$), $t(7) = –4.176$, $p = .004$ (Table 1).

Table 2. One-tailed paired samples t-tests comparing environment-specific durations between color and BW conditions (*n* = 4).

Paired Samples T-Test ▾

Paired Samples T-Test ▼

Measure 1		Measure 2	t	df	p
environment 1 color duration	-	environment 2 bw duration	−2.529	3	0.043
environment 2 Color duration	-	environment 1 BW duration	−7.863	3	0.002

Note. For all tests, the alternative hypothesis specifies that Measure 1 is less than Measure 2. For example, environment 1 color duration is less than environment 2 bw duration.
Note. Student's t-test.

To explore whether this effect varied by environment, additional one-tailed paired t-tests were conducted (Table 2). Results showed that in Environment 1, participants spent less time in color than in Environment 2 BW, $t(3) = –2.529$, $p = .043$. Conversely, in Environment 2, participants spent significantly less time in color than in Environment 1 BW, $t(3) = –7.863$, $p = .002$.

Discussion

The preliminary findings of this pilot study indicate that the experimental setup is suitable for examining the influence of visual conditions in VR. However, given the potential limitations of VR HMD design that may compromise experimental accuracy, careful measurements will be taken using a colorimeter, following the approach of a previous study by Rodríguez et. Al., "Colour Calibration of a Head Mounted Display for Colour Vision Research Using Virtual Reality"[19], which identified key challenges in achieving accurate color representation in HMDs and demonstrated the importance of luminance and chromaticity adjustments to ensure fidelity in color vision research. Initial results also point to a potential role of color in enhancing object-finding performance. As demonstrated by the significant difference in the time taken to locate the objects, participants performed better in the colored conditions than in the BW environments. This suggests that the lack of color cues may negatively affect search efficiency, increasing task duration. Furthermore, color environments generally sustained user attention more effectively than their black-and-white counterparts, which may have contributed to faster and more efficient object-finding. This study can be further explored by recruiting participants with more diverse visual perception, such as individuals with dichromatic color vision type, and various age ranges.

In conclusion, the study underscores the significant impact of color on object-finding tasks in VR. These findings not only contribute to the field of visual perception but also offer practical implications for VR design, particularly in creating environments that accommodate the needs of users with diverse visual abilities.

Conclusion

The methodology, which involved a VR object-finding game, demonstrated that participants performed better in colored environments, spending less time locating objects compared to black-and-white environments. As a pilot study, these preliminary findings suggest that the experimental design is effective for investigating visual influences on task performance in VR. Building on this, future research will involve a more diverse participant group to further explore how visual design elements, such as color, contrast, and luminance, can support accessibility and inclusivity in VR environments.

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