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ADVANCING COLOUR PERCEPTION: EXPLORING YOUNG CHILDREN'S COLOUR DISCRIMINATION IN MIXED REALITY

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ABSTRACT

One of the world's most famous pyramids is not located in Egypt but is on a music album cover by the band Pink Floyd. However, not a pyramid but a prism, the iconic image of a beam of light turning into a rainbow is a powerful symbol that captures the complexities of colour perception across cultures and individuals. This study examines how children can discern colour gradations in mixed reality (MR) environments, utilising the widely employed Farnsworth-Munsell 100 Hue Test. The MR version of the test, adapted for use with the Meta Quest 3, was evaluated with 52 children aged between 5 and 17 years. The results revealed significant differences in colour discrimination among age groups. Younger children had more difficulty distinguishing hues, particularly in the green-blue spectrum. The findings also demonstrate the applicability of MR-based colour assessments for younger children, providing a fast-screening alternative to traditional physical colour vision testing. The study's outcomes are conclusively synthesised, highlighting their implications for colour discrimination in educational settings.

KEYWORDS

Virtual Reality Color Vision Test, Mixed Reality, Children's Color Discrimination, Educational Technology, Farnsworth-Munsell Hue Test, Color Vision Screening

1. BACKGROUND AND RESEARCH AIMS

With the growing prevalence of mobile devices, screens, and VR/MR environments in daily life, many activities depend on digital representations. Musicians compose on tablets, children engage with digital textbooks, and meetings occur in virtual spaces. Studies show that head-mounted displays (HMDs) offer different colour rendering than traditional computer monitors or touchscreens. This is due to the proximity of the display to the user's eyes and the immersive nature of the experience (Toscani et al., 2019). For example, due to different viewing distances, a 24-inch Full HD monitor approximately corresponds to 63, a 4K monitor to 126, and the HMD Meta Quest 3, used in this study, to 20 pixels per degree. HMDs can also allow for specific control of external light with the video passthrough function, or even block environmental light entirely, which can influence colour perception differently from touchscreens and monitors (Siess et al., 2018).

Consequently, studying colour vision must extend to head-mounted displays (HMDs). Many jobs now require acute digital colour discrimination. In healthcare, accurate colour perception is crucial for diagnosis and interpreting colour-enhanced images (Ashton & Leppard, 2021; Brant & Helms, 2012). In transportation, it ensures safety by correctly interpreting digital signals (Blundell et al., 2020; Friedrich & Vollrath, 2022; Gibb et al., 2016; Mollon, 1982). The fashion industry relies on precise colour vision for quality control (Sekhri, 2022), and education benefits from understanding colour's impact on cognition and learning (Brooker & Franklin, 2016). Colour vision deficiency (CVD) affects about 1 in 12 boys and 1 in 200 girls worldwide (Birch, 2012; Gordon, 1998). Red-green colour blindness, the most common type, includes protanopia (lack of red photoreceptors) and deuteranopia (lack of green photoreceptors). Blue-yellow colour blindness (tritanopia) and complete colour blindness (achromatopsia) are rarer (Birch, 2012; Mollon, 1982; Paramei, 2012; Richardson et al., 2008). Given the impact of colour on learning (Brooker & Franklin, 2016; Duyan & Unver, 2016; Otto & Askov, 1968), this research focuses on colour discrimination skills in schoolchildren using mixed reality environments. The Farnsworth Munsell 100 Hue Test (FM100) is a key tool for assessing colour discrimination.

Used for over 70 years, it involves arranging 85 movable caps into a gradient to evaluate the ability to distinguish and arrange different shades of colour (Farnsworth, 1943) (Figure 1).

Figure 1. Physical Farnsworth–Munsell Hue Colour Vision Test. Courtesy of Gabriela P. (2019), Wikimedia Commons (CC BY 4.0)

The four colour gradient trays are (1) red-yellow, (2) yellow-green, (3) green-blue, and (4) blue-red. Many online versions of this test are simplified, using fewer than 20 hues per row. Widely used in industries to evaluate colour discrimination skills, the physical test serves as the basis for exploring mixed reality colour discrimination in schoolchildren.

1.1 Colour Discrimination in Children: Reality and Mixed Reality Environments

Understanding colour discrimination in children is critical, especially within educational settings where early cognitive and sensory development is paramount. Distinguishing between highly similar colours is necessary in various instructional contexts, such as fashion design education, where learners are required to recognise fine chromatic differences to develop harmonious palettes and achieve the desired visual effects (Quattrer et al., 2020), and in vision research utilising virtual reality environments, where colour accuracy and subtle variations in visual stimuli are essential for realistic perception and effective training (Ong et al., 2020; Toscani et al., 2019).

In this context, the physical FM100 test has been applied and studied across different age groups. Verriest et al. (1982) and Mäntyjärvi (2001) provided normative data indicating a developmental trajectory where colour discrimination abilities improve with age, peaking at around 19 years (Kinnear & Sahraie, 2002; Ling & Dain, 2018). The U-shaped performance curve identified by Kinnear and Sahraie (2002) reveals that colour discrimination improves from childhood, peaks in late adolescence, and declines in older age. This pattern underscores the need for age-specific colour discrimination assessment and intervention strategies. Additionally, the yellow-green and green-blue axes/trays have been found particularly challenging for children and adults, likely due to the physiological and perceptual properties of the human eye (Cranwell et al., 2015; Moreland, 1989). In educational contexts, colour is leveraged to enhance learning outcomes.

Cranwell et al. (2015) demonstrated that performance on the FM100 test is significantly related to nonverbal IQ, underscoring its cognitive demands. Research further indicates that strategically using colour in educational materials can improve memory retention and learning efficiency (Elliot & Maier, 2014; Witzel & Gegenfurtner, 2018). For example, Elliot (2015) and Kaya & Epps (2004) found that specific colours can influence cognitive performance and emotional states, impacting learning efficiency. Inclusivity in educational material design is crucial, incorporating high contrast, patterns, and other visual cues to accommodate variations in colour perception (Ali et al., 2021; Sushil et al., 2017). CVD studies highlight the importance of early screening to ensure that children are not disadvantaged in tasks requiring accurate colour perception (Chandak et al., 2017; Karunanayake et al., 2021). Adaptive learning strategies that recognise these variations allow educators to tailor instruction methods, employing assistive technologies or providing additional support for students who struggle with colour discrimination (Birch, 2012; Diachenko et al., 2022). Combining visual and textual information has been shown to enhance comprehension and retention (Mayer, 2020; Sweller, 2010).

In real-world settings, aside from educational material, the use of colour in classroom design has also shown a significant impact on children's attention and engagement (Duyan & Unver, 2016; Gaines & Curry, 2023). In digital learning environments, the quality and type of display can affect colour perception as well, making it crucial to design digital content that is accessible and effective for children with and without CVD. Research in colour discrimination testing on computer screens confirmed the age-related performance curve found in the physical tests (Kinnear & Sahraie, 2002), with colour discrimination skills peaking in late adolescence while declining in older adults again (Ling & Dain, 2018; Paramei, 2012). Emerging technologies offer adaptable colour control, such as entirely simulated learning environments in virtual and mixed reality scenarios, allowing the real world to pass through the HMD. However, studies show that colour attributes in immersive VR environments can impact cognitive performance, as do different interaction variants (Jost et al., 2019; Xia et al., 2023).

Regarding colour perception and discrimination skills in 3D immersive environments, Cwierz et al. (2021) conducted an FM100 colour test in fully calibrated VR for adults. They found that both the physical and VR tests are similarly functional, though the VR test was somewhat more difficult, likely due to the challenges of using HMDs. In alignment with the higher cognitive demands found for VR learning tasks, their results also highlight the potential for viable colour discrimination assessments in immersive 3D scenarios.

Understanding colour discrimination in children across various real-world, screen and mixed reality settings is essential for developing effective educational strategies and materials. The FM100 test presents as a critical tool for this purpose. With adaptations for quicker assessments oriented on the digital variants offered online, it could provide an accessible rapid-screening approach. In an applicable form, it could help identify exceptional colour vision skills early in school or during engaging MR experiences tailored to each age group and provide for more controllable assessment settings via HMDs.

1.2 Research Objectives

To explore colour discrimination skills of school children and learn more about the applicability of colour vision assessment in immersive digital environments. This study extends traditional colour vision research by examining how colour discrimination skills vary between younger and older school-age children in a mixed reality environment experienced through an HMD and its relation to physical colour vision testing. The FM 100 Hue Test serves as the foundation for the study that explores two research objectives:

1. Explore colour discrimination skill differences between younger children (ages 5-9) and older children (ages 10-17) when engaging in a mixed reality colour sorting task based on the FM100 test. Specifically, the study will examine colour differentiation ability in the four colour gradient trays (Red-Yellow, Yellow-Green, Green-Blue, Blue-Red) and evaluate total error rates.
2. Investigate the overall tendency in age-group colour discrimination change between the mixed reality variant and the conventional FM100 test. Therefore, assessing the relation of physical and mixed reality colour discrimination performance, as experienced through HMD, and its applicability as a fast-screening tool for colour vision at schools and extracurricular events.

2. EMPIRICAL RESEARCH METHODOLOGY

2.1 HMD Specifications and Fast-Screening Considerations

Computer screens employ colour management and colour spaces to display colours accurately. Without proper colour management, colours like "Maximum (255,0,0) red" can vary significantly between screens due to differences in subpixels and pixel density[1]. In HMDs, pixel density further affects colour accuracy, impacting how closely pixels are placed. Colour spaces, such as sRGB and Adobe RGB, define the range of displayable

[1] https://developer.oculus.com/resources/colour-management-guide

colours and white points. The white point is the reference white used in the colour space, indicating the colour temperature of white. For example, sRGB uses a D65 white point, corresponding to a colour temperature of approximately 6500 Kelvin, resembling average daylight.

Notably, Oculus and Meta Quest HMDs use a D75 white point, corresponding to a colour temperature of approximately 7500 Kelvin. This higher colour temperature results in slightly bluer tones than the standard D65 white point used in sRGB displays. Despite consumer displays, including HMDs, not being ideal for absolute colour accuracy, they are suitable for relative colour difference assessments due to their close adherence to the sRGB Rec.709 standard. The Meta Quest 3 HMD was selected for its accessibility, advanced hardware, and affordability, making it suitable for large-scale colour vision tests and fast-screening at schools and events. Other HMDs, like the Apple Vision Pro, offer more advanced technology but are less accessible and significantly more expensive. Features of the Meta Quest 3, such as hand-tracking, offer intuitive interaction with virtual objects important for an MR FM100 test, such as picking and placing colour caps for sorting and higher quality video passthrough of the surroundings for spatial orientation reducing risks when many children group or queue to take part in the colour vision assessment event. The Meta Quest 3 weighs 515g, has 2064 x 2208 pixels per eye, a 120Hz refresh rate, and a 110° x 96° field of view with an RGB stripe subpixel layout that contributes to a consistent arrangement of red, green, and blue subpixels[2].

2.2 Creating and Configuring the Mixed Reality Colour Discrimination Task

The colour test application was developed using the Unity game engine and deployed as an Android APK for the Meta Quest 3. Various plugins were utilised to implement robust hand tracking and enable passthrough functionality, including the XR Interaction Toolkit, Open XR, and AR Foundation. The application aimed to be as physically accurate as possible by using the default Linear colour space. Light settings were calibrated to be close to the D65 standard, providing a neutral white light without an intense colour temperature that could introduce an unwanted tint to the scene. The test setup was minimalistic to avoid distractions. It consisted of a grey table, a wooden board on top, and 10 cap slots per colour gradient tray. Each of the four colour gradient trays, aligned with the physical FM100 test, was presented separately to the participant for sorting (Figure 2).

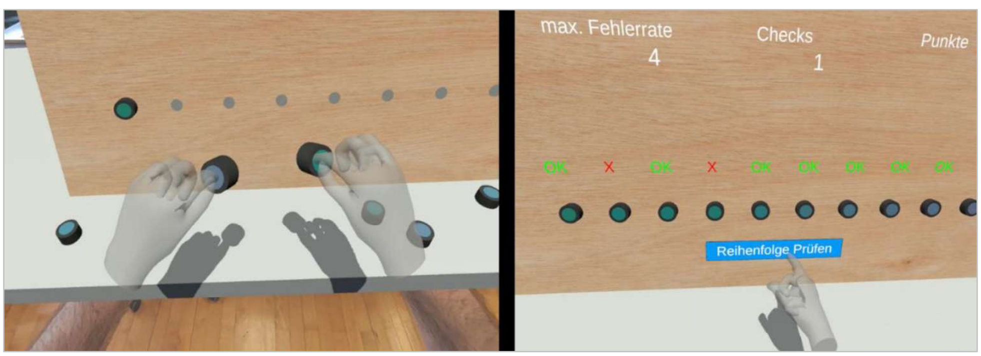

Figure 2. Mixed reality colour vision task based on the FM100 hue test with reduced colour caps (40 from 85) for quick screening with school children. Image captured from the HMD by the authors

At the start of each session, the first and last caps were pre-placed on the board. Participants then picked up one of the remaining eight caps on the table and placed them to create a seamless colour gradient per tray by judging the colour. Thanks to the activated passthrough feature, the real-world surroundings were visible during the MR setup. Interaction with the scene was intuitive, as hand tracking was used for picking and placing the caps, eliminating the need for additional controllers. Participants could grab and place the caps using their hands, similar to the physical FM100 test (Figure 2, left). A sound effect played when a cap was correctly placed in a corresponding slot on the board, with different tunes indicating correct or incorrect final solutions.

Caps could be re-arranged if necessary. Once all caps were placed, the tray could be checked, indicating which pins were correctly placed. Participants could then adjust the placement of the caps and perform another check. After sorting all four trays correctly, a final high score was calculated and displayed to the participants.

[2] https://developer.oculus.com/quest

Each time the app started, the first and last caps were placed on the board. All that was left to do for the participant was to pick up one of the remaining 8 caps on top of the table and place them accordingly to create a seamless colour gradient per tray by judging the colour. While doing this task, the real-world surroundings can be seen in this MR setup thanks to the activated passthrough. Interacting with the scene was intuitive, with hand tracking allowing the pick and placement of the caps, and no additional controllers were required.

As with the physical FM100, participants could grab and place the caps using their hands (Figure 2). A sound effect would play when a cap was placed in a corresponding slot on the board. A different tune would play, depending on whether the final solution was correct or wrong.

If necessary, caps already placed could still be removed and placed again at a new location. If all caps were placed, this tray could be checked to indicate which pins were placed correctly. The user could then take action to adjust the placement of the pins again and perform another check. When all 4 trays were sorted correctly, a final high score was calculated and shown to the participants. The MR app was based on a smaller variant of the FM100 hue test, commonly used for online colour tests, and is also available on the official physical test publisher's website[3]. In this variant, there are 10 colours with a fixed start & end point and 4 different colour trays:

Table 1. Mixed reality FM100 colour gradients and cap colour values by tray (hexadecimal code)

red-yellow	b2766f	b17466	ae725f	a8745a	a87452	a8794e	a97e4c	a78244	a28946	9d8e48
yellow-green	97914b	8d9352	86955c	7e9760	7c9567	699a71	649a76	5b947a	589480	529687
green-blue	4e9689	4c9691	4a9696	4a9698	52949f	6090a5	688fa7	6c8aa6	7489a7	7b84a3
blue-red	8484a3	8d85a3	9483a0	99819d	9f7f98	a9798b	ae7787	b1757f	b3757a	b37673

We chose this setup because the completion time is quicker and more fitting to fast-screen queues of school children waiting to participate, compared to a full FM100 colour set with more than twice the number of caps to place.

2.3 Research Design and Data Collection

The field test was planned to be conducted during a big event at our university, showcasing research practices and projects to young children. The colour test setup was situated in one of the many rooms featuring various projects. Over six hours, visitors continuously participated in the colour test, often forming a line to wait for their turn. Initially, three stations with HMDs and instructors were available, but due to higher-than-expected demand, we later switched to two stations to allow one HMD to recharge.

The setup included three Meta Quest 3 HMDs, with tablets mirroring the participants' views. The three instructors assisted the children with putting on and adjusting the HMDs for comfort. A computer screen displayed a leaderboard with the top 10 best scores, and another showed a loop of a typical playthrough of the colour test app. The high score calculation considered error rate, error distance, time, and submission count. While not subjected to scientific evaluation, the high score was included to engage young participants and encourage participation.

When first starting the app, a disclaimer and opt-in screen were displayed on the HMD and the mirrored tablet screen, explaining what data we collect and how we use it. For children below 14, the parents also had to agree to participate. Furthermore, the participant could input a nickname and choose an age group range. We offered 8 age groups from 5 to 64 years in case some parents and grandparents also want to participate. The order in which the four gradient trays were presented to each participant was calculated randomly. The first and last caps of the presented gradient were already fixed in place, and the other eight colour caps were randomly spawned in the front area of the table (Figure 2, left). The participant could pick up each of them, judge their colour shaded, and place it in a socket at the decided place in the gradient. After completing all 4 colour trays of the FM100, the headset sent its data to our server secured by https protocol. It would then be visible on the computer screen, and the young participants could see their rank. The HMD was ready for other visitors to participate. In accordance with the *first* research objective, it was hypothesised that there would be a difference between the age groups

[3] https://www.colorlitelens.com/images/huetest/Farnsworth100.html

regarding MR colour discrimination performance across the colour trays. Respectively, the null hypothesis for the field study was established as:

$H_{0:}$ 'There is no significant difference in colour discrimination error rates between younger children (ages 5-9) and older children (ages 10-17) for each colour tray (RedYellow, YellowGreen, GreenBlue, BlueRed) and in total error rates.'

Moreover, concerning the *second* research aim, the colour discrimination between the younger and older children was expected to show similar improvement (mean error percentage improvement) in the MR colour test compared to the findings of the traditional physical FM100 with a full colour cap set. For this, the comprehensive existing results from literature were screened (Kinnear, 1970; Kinnear & Sahraie, 2002; Mäntyjärvi, 2001; Verriest et al., 1982) with finding the results of Kinnear and Sahraie (2002) providing data for the respective age-groups for comparative descriptive analysis.

3. RESULTS

3.1 Participation

Many of the participants were very young (age-group 5 to 9) and used an HMD for the first time. After a short introduction, the participants found it easy to use and understand, thanks to the intuitive hand tracking and MR passthrough (Figure 3).

Figure 3. Mixed reality colour vision task based on the FM100 hue test with reduced colour caps (40 from 85) for quick screening with school children. Image captured from the HMD by the authors

We removed participants who did not finish all rounds or had already done the test before. This is an important step because, in contrast to the traditional test where there is only one final check, in our MR variant, each tray could be readjusted until all colours are at their correct location on the board before progressing to the next gradient. After cleaning, 52 valid data sets were put forward for analysis (Table 2).

Table 2. Participation in the FM100 MR fast-screening colour vision app for school children

Age group	*participants (n)*	*red-yellow*	*yellow-green*	*green-blue*	*blue red*	*total*
5-9	19	55.47	56.11	50.79	56.68	219.05
10-17	33	48.82	53.27	57.48	56.42	216.00

Note. The table shows the number of participants per age group and their mean completion time (seconds) for each colour tray and the total

3.2 Mixed Reality Colour Discrimination Performance

For analysis regarding the first research aim, statistical analysis ($\alpha = 0.05$) involved independent samples *t*-tests of the mean error rates per cap using IBM SPSS Statistics version 29. Stratified bootstrapping (10,000 samples, bias-corrected and accelerated) was applied to account for non-normality in the data distribution (Field, 2018), as indicated by the Shapiro-Wilk test ($p < 0.05$) with equality of variances assumable for all measures (Levene's test $p > 0.05$). The descriptive statistics and results, including bootstrapped standard errors, *t*-statistics, *p*-values, and 95% confidence intervals (*CIs*), are summarised in Table 3.

Table 3. Mean error rates and statistical results of MR colour discrimination performance between age groups

Colour tray	*M* per cap and (total) [5-9]	*M* per cap and (total) [10-17]	*M diff.* per cap	*95% CI lower*	*95% CI upper*	*M total* change in %	*t*	*p*	*Cohen's d*
total	0.39 (12.6)	0.30 (9.64)	-0.09	-0.20	0.02	-23.7	-1.72	0.10	-0.48
red-yellow	0.24 (1.95)	0.25 (2.00)	0.01	-0.13	0.14	2.56	0.10	0.92	0.03
yellow-green	0.34 (2.74)	0.26 (2.09)	-0.08	-0.24	0.07	-23.7	-1.05	0.30	-0.31
green-blue	0.57 (4.53)	0.36 (2.88)	-0.21	-0.35	-0.05	-36.4	-2.70	0.01	-0.79
blue-red	0.43 (3.42)	0.33 (2.67)	-0.09	-0.26	0.07	-21.9	-1.12	0.26	-0.31

Note. Mean error rates per cap are calculated per movable colour cap: 8 per tray, 32 in the total MR FM100

The results revealed significant differences between the two age groups for the green-blue (tray 3) error rate per cap. The younger children show a significantly higher mean error rate per cap ($M = 0.57$) compared to the older children ($M = 0.36$), $t = -2.7$, $p = 0.01$, with a moderate to large effect size of Cohen's $d = -0.8$. In the other colour gradient trays and the overall mean error rate, the colour discrimination capability was not statistically different between the two age groups (Figure 4).

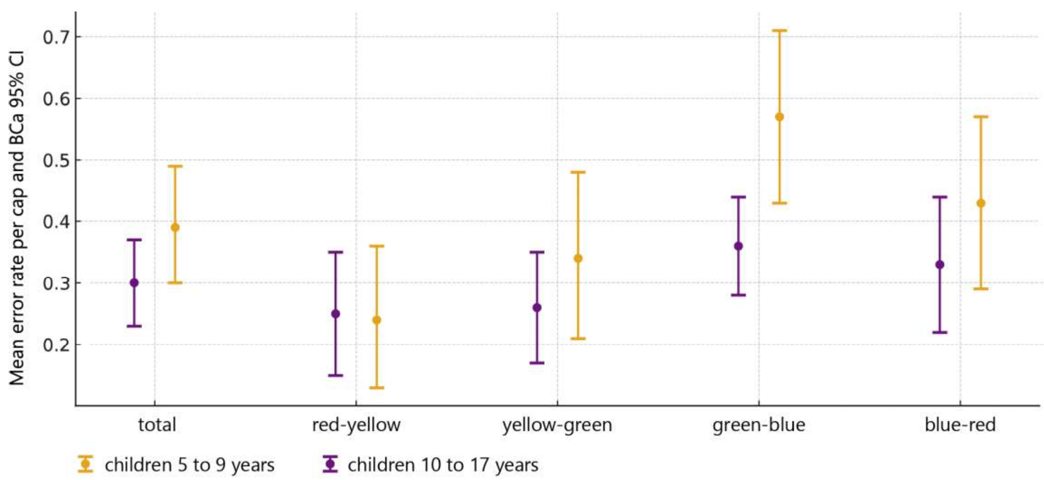

Figure 4. Mixed reality colour discrimination performance between children aged 5-9 and 10-17 years

As the MR colour differentiation of the younger children (5 to 9) differs significantly in the gradient from blue to green, the results suggest rejecting H_0 and indicate an age-related improvement, particularly in discriminating these colour shadings towards an older age between 10 and 17. Notably, a tendential improvement of colour discrimination skill was reflected in the results for all colour gradients of the FM100 test, except the red-yellow gradient (Figure 5).

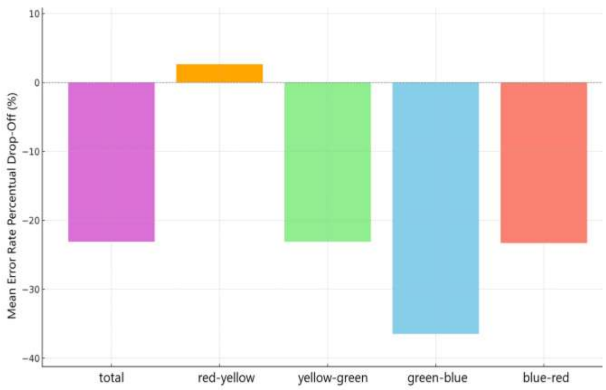

Figure 5. Percentual drop-off in the mean error rate between children aged 5-9 and 10-17 in total and within the colour trays of the MR test

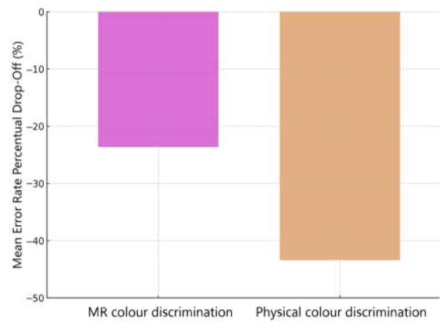

Figure 6. Percentual drop-off (total mean error rate) from ages 5-9 to 10-17; MR test compared to Physical FM100 by Kinnear and Sahraie (2002)

Regarding the second research objective, the descriptive analysis (Figure 6) reveals a pronounced drop-off in mean errors for both the MR colour discrimination test (M_{change} = -23.7) and the physical FM100 test across all 85 colour caps (M_{change} = -43.4), highlighting age-group improvement. The improvement is more prominent with the physical FM100.

4. DISCUSSION

4.1 Implications Regarding Children's Colour Discrimination Skills in Education

The findings on the research objectives of this study both provide implications for educational practices, particularly in how colour discrimination skills are assessed and understood in school-age children within mixed reality environments. As established in previous literature, colour plays a crucial role in educational settings by enhancing learning outcomes and cognitive processes (Brooker & Franklin, 2016; Elliot & Maier, 2014).

Regarding the *first research objective*, the current study extends this understanding by demonstrating that children's ability to discriminate colours, especially in challenging gradients like green-blue, improves with children's age in MR environments in line with the findings of both physical (Kinnear & Sahraie, 2002; Verriest et al., 1982) and digital screen-based (Ling & Dain, 2018) colour discrimination tests. Educational implications arise from the observed differences in colour discrimination skills between younger (5-9 years) and older (10-17 years) children. Specifically, the significant differences in the green-blue gradient suggest that educational interventions should consider age-specific strategies for teaching and assessing colour perception abilities (Cranwell et al., 2015). For instance, early screening of colour discrimination skills in MR environments can identify children who may benefit from targeted educational support or interventions tailored to their developmental stage. The results underline previous findings that green-blue colour hues pose a challenge for colour discrimination (Moreland, 1989). This study particularly highlights these difficulties for younger children between the ages of 5 and 9, with significant improvements observed in children aged 10 to 17, consistent with results from screen-based colour discrimination studies (Ling & Dain, 2018). In addition, the results demonstrate that this holds true also for mixed reality scenarios that blend digital colour renderings with real-world passthrough visuals.

With the *second research objective*, the study further explored this comparability of MR-based colour discrimination assessments with the traditional physical FM100 test. While the error rates were generally higher in the MR environment compared to the physical test, the drop-off in error rates between age groups was less pronounced in MR than in the physical FM100. This finding aligns with previous research in virtual environments, which also reported higher error rates than physical testing methods (Cwierz et al., 2021). The lower drop-off in error rates between age groups in MR can be attributed to the challenges posed by MR environments, such as interacting with virtual objects. However, unlike fully synthetic VR, MR allows for more natural interaction using hand-tracking technology together with the visual perception of real-world elements, which may facilitate better performance in colour discrimination tasks compared to fully rendered VR settings and using controllers. Future research can explore insightful comparative studies between VR and MR FM100 assessments, building on the contributions of this study. Furthermore, this study's findings demonstrate the potential of an accessible MR-based test based on the simplified FM100 as a fast-screening tool for colour discrimination in school settings and extracurricular events. Despite higher error rates compared to physical tests, the expected drop-off in error rate between age-groups and the corresponding profile within the four colour trays support the suitability of the MR test for screening of exceptional colour discrimination skills and CVD in scenarios showcased in this study.

MR colour vision screening using a commercial HMD, therefore, offers a practical alternative for quick assessments, aligning with the needs of educational environments where efficiency and accessibility are crucial (Chandak et al., 2017). The comparable drop-off in error rates and expected results across age groups and colour gradients shows that using an MR test with a commercial HMD can effectively screen children's colour discrimination challenges. This highlights the applicability of MR-based testing in educational screening protocols using the demonstrated configuration, especially since the average completion time for the MR FM100 test is less than four minutes per child (Table 2).

4.2 Limitations

While this study provides valuable insights, it also has some limitations. Our MR setup differed from the traditional FM100 test by including a timer, high score display, and larger cap distances for hand tracking. We used fewer colours for an accessible, child-friendly variation, which might affect sensitivity. Each of the four colour trays was presented individually and could be repeated with feedback until correctly sorted, potentially impacting results. We did not pre-screen for CVD in the children, while the physical FM100 study held for comparison excluded these individuals. This may contribute to the lower error drop-off rate in our MR test. While the MR CVD test, as demonstrated in this study, can provide for rapid pre-screening of colour discrimination skill peculiarities, it is not a medical application. Thus, detected anomalies require follow-up and further thorough investigation using the physical FM100 test or other standard diagnostic procedures. Despite these limitations, the study suggests promising potential for MR-based colour discrimination testing, highlighting the need for further research with larger, diverse samples and controlled environments.

5. CONCLUSION

This study explored colour discrimination skills in schoolchildren using mixed reality (MR) environments compared to traditional FM100 tests. Significant age-related differences were found, especially in the green-blue colour gradient, with younger children showing higher error rates. These findings underscore the need for age-specific educational strategies. Despite the expected higher overall error rates in MR tests, the consistent patterns of age-related improvement indicate MR's potential as a fast-screening tool for colour vision in educational contexts. The MR test's accessibility and engaging format, associated with the fast completion time of under four minutes, make it a practical alternative to traditional methods. The study advances our understanding of colour discrimination in children within MR environments, offering valuable insights for educational practices. Integrating MR technology enables educators to identify and support diverse colour perception abilities, enhancing learning outcomes and cognitive development. Future research should further explore and refine its applicability across different age groups and settings.

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