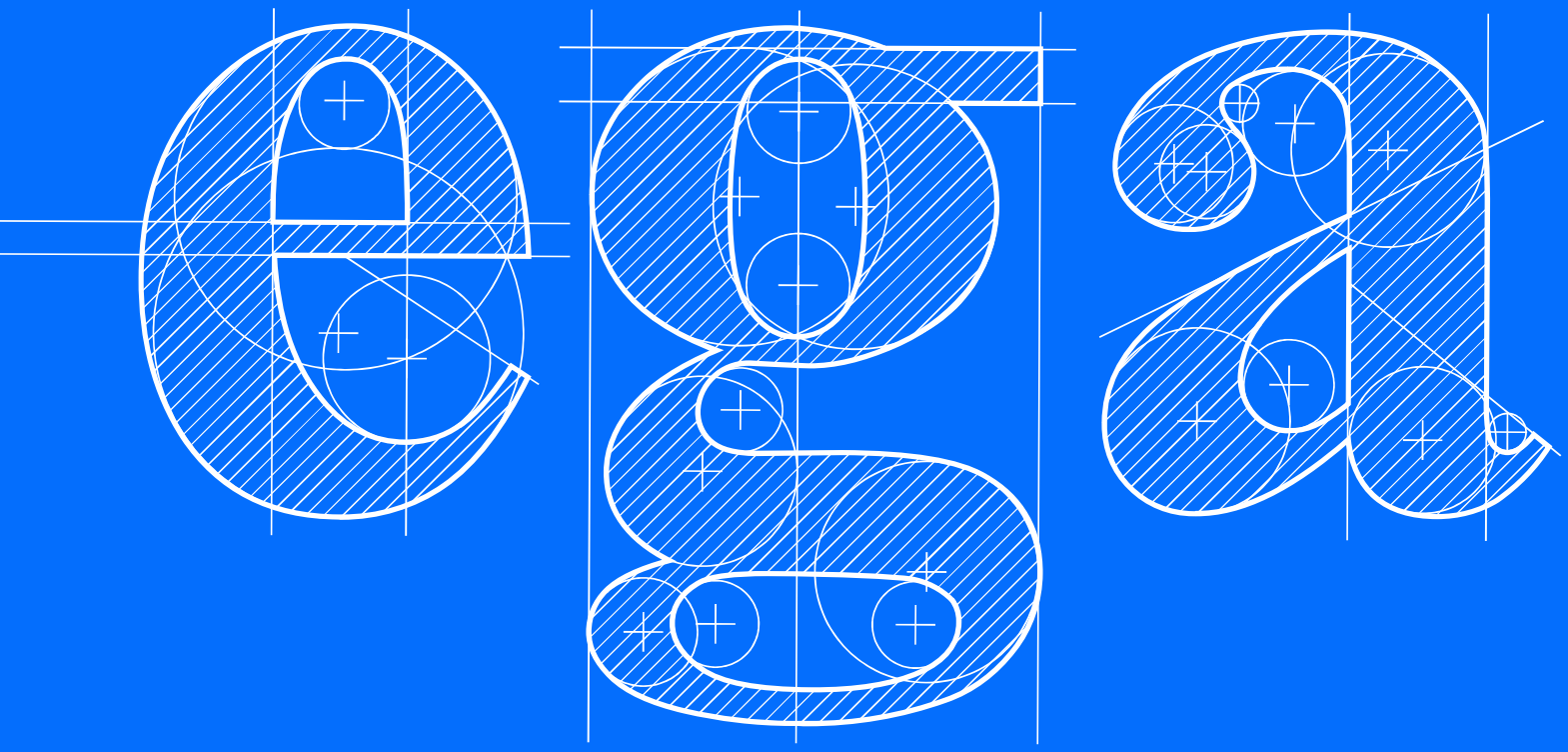

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5. HACER. FACER. FARE. MAKING.

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Virtual reality to evaluate the amplitude of interiors with different colors

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Figure 1. Color composition in a VR interior inspired by Joseph Albers' Homage to Square (1951). Source: authors.

Abstract

Artists and architects since the Modern Movement, like Albers or Le Corbusier, experienced in their artwork that color is important for depth and amplitude estimation, but without a scientific background. Investigations have commonly addressed the illusion of color depth in 2D, namely chromostereopsis, and more recently the evaluation of egocentric distances in real scenarios compared with VR, but there are scarce results on the role of color in the distances and amplitude evaluations of interior architecture. This text aims to describe two methods that we implemented in the MCSL at RIT, to obtain an objective numerical estimation of the amplitude variation of a room because of the color and using VR. This methodology required a reliable colorimetric control of the visualization devices HMDs and the psychophysical conditions of the observers. Results indicate that VR with HMDs for perceptual matching tasks and visually directed motor actions, is an accurate tool to evaluate the amplitude of virtual interiors with different colors, despite the color differences did not cause an important effect on perceived size. The existence of some visual cues related with the geometry of the rooms might be in the roots of this result and should be reconsidered in the future.

Keywords

Color; architecture; virtual reality; size; Albers

1. Introduction

"Color is a complement to architecture. It is useful to enlarge or reduce a space. Moreover, it is useful to add that touch of magic that the place needs" ["El color es un complemento para la arquitectura. Sirve para agrandar o reducir un espacio. Además, es útil para añadir ese toque de magia que el lugar necesita."] (Barragán 1985, p. 106)

Historically, color in architecture has been reported to influence the perception of amplitude in an interior and alter the apprehension of its size or proportions, setting a contradiction between the actual dimensions of the space and those perceived: height, width, length (Hayten 1960, pp. 22–23; Mahnke 1996). Artists like Joseph Albers (1982) described some effects of the interaction of colors in terms of their spatial depth in 2D, while architects such as Le Corbusier described the ability of blue hues to give amplitude and red to diminish it (Le Corbusier & Rüegg 1997, pp. 114–115), applying these perceptual phenomena in some of his emblematic works like *Les Quartiers Modernes Frugès* in Pessac (France, 1924).

This matter is particularly important for the adaptation of existing architectures with a given size, a trend in European policies, which are directed towards the efficient use of resources for adaptation to change. Color is an unavoidable and economically efficient aspect to increase the quality of living in interiors and has been reported as an important feature to influence the visual perception of amplitude (Stamps 2010a).

The perception of depth depends on monocular cues such as the interposition, linear perspective, relative and known size, texture gradient, light and shadow distribution, aerial perspective and so on, together with binocular cues that depend on the horizontal disparity of two retinal images (Bai *et al.* 2017). Therefore, a greater disparity range represents more efficient depth perception, and color demonstrates to act as an important cue to enhance stereoscopic perception (Bai et al., 2017). Of particular interest is the phenomenon of *chromostereopsis*, which is an illusion of depth due to chromatic contrast. It is usually perceived with red and blue and is commonly attributed to transversal chromatic aberration (TCA): red rays are less refracted than blue rays, inducing a disparity between the red and blue images on the retina (Séverac Cauquil *et al.*, 2009).

Despite the interest of the experiments and artistic works indicated, their field of application has usually been limited to flat representations in two dimensions (Guibal & Dresp 2004), and their results are insufficient to evaluate the influence of color in surrounding 3D spaces, as happens in interior architecture. There was a methodological limitation to evaluate the color of an architecture on a 2D image, which some researchers tried to solve with scale models (Gyu Park 2014).

Nowadays, the digital 3D visualization systems using head-mounted displays (HMDs), are improving the traditional methodologies for the study of the perception of spatial distance, both by using virtual reality (VR) (Stamps 2007), and augmented reality (AR) (Berning *et al.* 2014, Schmidt *et al.* 2016). Some of the most relevant studies with VR correspond to Stamps, who has investigated the influence in spatial distance perception of some physical design variables such as the height of the perimeter, the horizontal surface (Stamps 2010b), the porosity of the contours, the proximity of the perimeter (Stamps 2010a), but never color and its perceptual variables in a specific way, probably due to the technical difficulty to manage the color reproduction on electronic devices accurately. Other VR studies with simulated architectural interiors have focused on attributes of the space such as size, lighting, position of windows (Bokharaei & Nasar 2016), as well as behavioral opportunities in the space that affect perceivers' spatial impressions of the environment (Meagher & Marsh 2014).

Feldstein, Kölsch and Konrad (2020) made an extensive literature review about experiments for distance judgement in VR indicating 3 main methods: (1) verbal estimation of distances that typically require participants to numerically judge the absolute distance (Sánchez-Riera *et al.* 2022); (2) perceptual matching tasks that demand the ordinal or relative comparison of two or more distances, and (3) visually directed actions, such as blind walking or blind throwing (Andrus *et al.* 2014). Lin *et al.* (2011) demonstrated that observers tend to walk a greater distance in physical reality compared to VR, being more accurate with the presence of an avatar that reproduces the observer's movements. Moreover, the judgement for distances in real environments is more accurate for distances of up to ten meters, with the exception of verbal estimates that tend to show some underestimation also at closer distances (Feldstein *et al.* 2020). Regarding the composition of the virtual environments, recent works highlight the importance of photorealistic graphical rendering, realistic ground texture and other pictorial depth cues, such as linear perspective, foreshortening, and texturing, to improve distance perception and distance judgement (Feldstein *et al.* 2020).

In brief, color has historically been indicated to be an important feature in depth (2D) and amplitude (3D) perception by artists and architects. In the experimental field, investigations have addressed the illusion of depth in 2D due to chromatic contrast, namely *chromostereopsis*, and more recently the study of egocentric distances with a given object, comparing real with virtual distances. Nevertheless, scarce findings in 2D have been transferred into 3D environments and there is a lack in experimental investigations, on the role that color has in the perception of the distances and amplitude of interior architecture.

The aim of this text is to describe a method to evaluate the influence of color in the perception of the dimensions of an interior architecture using VR, to obtain an objective numerical estimation of the amplitude variation because of the color. This methodology requires a reliable colorimetric control of the visualization devices HMDs and the psychophysical conditions of the observers.

2. Description of two experiments to evaluate color amplitude with VR

Different to previous experiments about spatial distance, our experiment did not to work with a digital twin of an existing architecture comparing real vs. virtual interiors (Sánchez Riera *et al.* 2022), but will work with the dimensional comparison of digital vs. digital scenarios. We took this decision to extend the number of colors evaluated, and because in real interiors it is difficult to have rooms with identical visual conditions painted in different colors.

We set two experiments that included perceptual matching tasks and visually directed motor actions. The architectural models were drawn with Autodesk AutoCAD, materials definition and simulation of lights with Autodesk 3ds Max, and the Unity Virtual Reality engine was used for the visualization with a HMD. The VR model was the interior of a room with common dimensions in housing, and no visual cues for distance estimation others than the edges of the limits and egocentric position. Rendering different colors, we obtained 38 different scenes.

In *experiment 1*, participants were placed in two interior rooms of identical proportions but with different colors that shared a common wall with a door (Fig. 2). Room A had fixed dimensions of 6.9 x 2.4 x 2.5 m and room B had randomized bigger or smaller dimensions, but maintained the same proportions as A. Participants wore a HMD with a sensor that tracked their position. and could move through the virtual rooms, navigating the environment by physically walking. With the help of a hand control, participants could increase or reduce the size of room B until it looked like room A. The final scale of both rooms was recorded, and a new variable defined as S_{xyz}=scale room A/scale room B. Accordingly, S_{xyz} >1 indicated that color B tended to increase the amplitude of a room compared with color A, while S_{xyz} <1 indicated that tended to reduce the amplitude.

In *experiment 2*, participants were randomly placed in the interior of a room measuring 6.9 x 2.4 x 2.5 m, with all the surfaces in white, walls and ceiling, except for one of the walls that was in the east or west position, which had a different color (Fig. 3). Again, participants wore a HMD with a sensor that tracked their position and could move through the virtual room, navigating the environment by physically walking. Participants were asked to move to the center of the room. Their final position with respect to the walls was recorded, and a new variable described as: S_x =longitudinal distance to the white wall/ longitudinal distance to the painted wall. Accordingly, S_x >1 indicated that the color tended to recede and therefore increase the longitudinal distance compared with white, while S_x <1 indicated that tended to reduce the longitudinal distance.

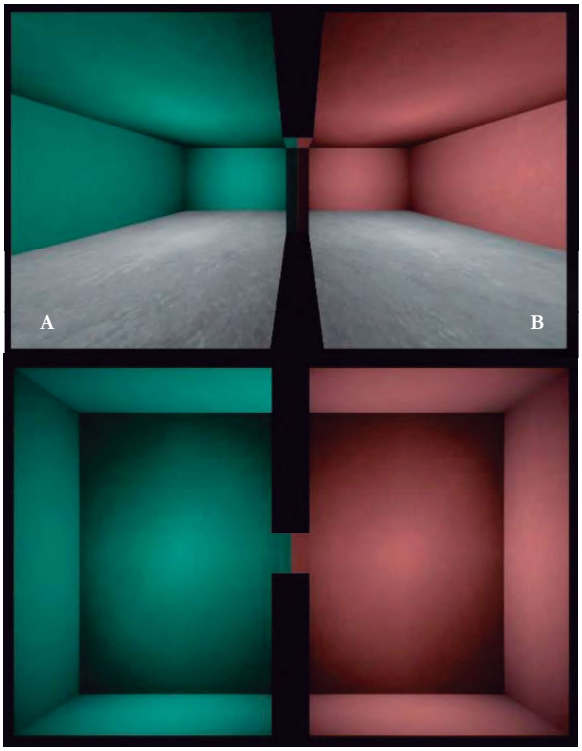

Figure 2. Frontal perspective (top) and cenital perspective (bottom) of a scene from experiment 1. Room A has a fixed dimension while B appears with a random scale. Source: authors.

Our VR system involved a stereoscopic HMD Htc VIVE, with two tracking sensors and a control center (computer). The device was characterized to assure that the colors rendered on the glasses were as similar as possible as those of the Munsell notation. Regarding the colors, the floor of the rooms had the same finishing in every scene (except in the variegated), with a neutral gray (N4) and a texture simulating concrete with fixed size. The walls and ceiling simulated plaster with a fixed texture size but different colors. These color ranges responded to a selection criterion based on the Munsell color notation and the literature review, and included monochromatic finishing (Fig. 2) as well as variegated compositions (Fig. 1). Regarding the lighting of VR interiors, the virtual luminaires were equivalent to a D65 white dot spherical omnidirectional light, with the 6 surfaces of the room (floor, ceiling and 4 walls) having uniform lighting.

Experiments 1 and 2 were run in the interior of an empty room in the Munsell Color Science Laboratory at

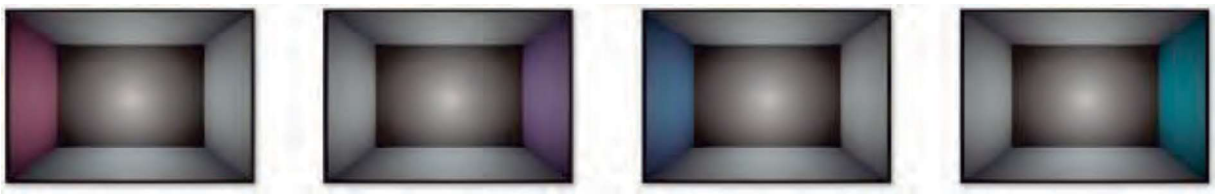

Figure 3. Frontal perspectives of some scenes from experiment 2. The participant is asked to move to the center of the room, navigating the space by phisically walking, and placing at the same distance to the east and west wall. Source: authors.

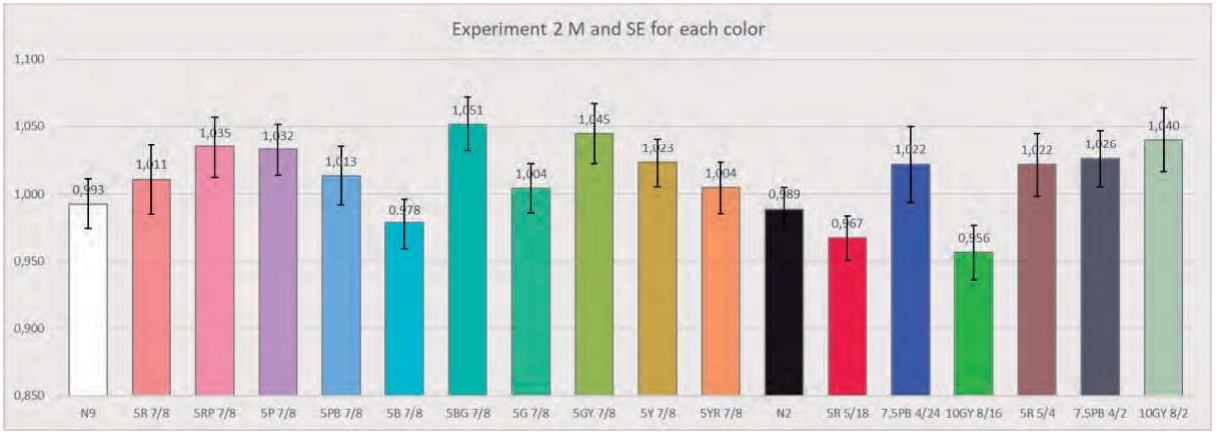

Figure 4. Average scale S_{xyz} for the 18 scenes of experiment 2. Values are very close to 1, indicating a noticeable accuracy in the evaluation of the distances between east and west wall by participants in experiment 2. Source: authors.

Rochester Institute of Technology by a collective of 27 participants (15 female, 10 male, 2 non binary), who were on average 27 years old (SD=6.1; [19-44 y/o]), recruited via the XXX System. Every participant completed the 2 experiments with an evaluation of 38 scenes in approximately 40 minutes, including two breaks.

3. Results and discussion

For experiment 1, the results indicate that room B compared with A for the 20 scenes has an average scale S_{xyz}=1.012 (SD=0.014, SE=0.003). This means that, on average, the colors in room B make it look 1.2% bigger in width, length and height, in comparison with the colors in room A. Therefore, we can observe that VR is an accurate tool to evaluate the dimensions of two VR interiors in an experiment with perceptual matching tasks to adjust the sizes of length, width and height of two room with different colors.

For experiment 2, the results indicate that a color rendered on a wall in a white interior for the 18 scenes has an average scale Sx=1.01 (SD=0.03, SE=0.01) (Fig. 4). This means that the range of colors chosen, on average, make the room look 1% bigger in length, in comparison with a white color. Therefore, we can observe that VR is an accurate tool to evaluate the length distances in a VR interior, in an experiment with visually directed motor actions to place oneself in the center of a room with a wall painted in color.

4. Conclusions

Investigations have commonly addressed the illusion of color depth in 2D, namely chromostereopsis, and more recently the evaluation of egocentric distances in real scenarios compared with VR, but there are scarce results on the role of color in the distances and amplitude evaluations of interior architecture. We have described two methods implemented in the Munsell Color Science Laboratory at RIT, to obtain an objective numerical estimation of the amplitude variation of a room because of the color and using VR.

Results indicate that VR with HMDs for perceptual matching tasks and visually directed motor actions, can be an accurate method to evaluate the amplitude of virtual interiors with different colors, despite the fact that color differences did not cause an important effect on perceived size. The existence of some visual cues, particularly in experiment one, like the possibility to compare the position of some edges in both rooms simultaneously, might be in the roots of this result and should be taken into consideration for future experiments.

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Juan is PhD. architect, full-time associate professor, sub-dean of research in the School of Architecture-UPV, has been Fulbright Visiting Scholar at RIT, and is member of the Color Research Group in Architecture of the IRP-UPV. Juan is author of the book Color for Architects (PAPress, 2019), being specialist in modern and contemporary architecture. Juan has participated in competitive research projects about color restoration, color integration of buildings, and color in interior architecture to improve well-being and performance.

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Dr. Mekides Assefa Abebe received her Ph.D. from the University of Poitiers, France, specializing in "Signal and Image Processing." Her doctoral research focused on the field of High Dynamic Range (HDR) imaging, and she successfully completed her dissertation in this area. Presently, she holds a permanent researcher position at the Color and Visual Computing Laboratory of NTNU in Norway. Concurrently, she is working as a Visiting Assistant Professor at the Munsell Color Science Laboratory of RIT in the United States. In addition to her expertise in HDR imaging, Dr. Abebe's research interests encompass a wide range of topics, including color and material appearance reproduction, computer vision, and other related areas.

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