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Luminosity thresholds in projection mapping under environmental lighting

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Projection mapping alters the visual appearance of objects by projecting images onto their surfaces. Traditionally, its application has been limited to dark environments because the contrast of the projected image diminishes in environmental lighting. This often results in the target appearing self-luminous, creating a perceptually unnatural effect. Recently, however, projection systems have been developed that maintain high contrast even in well-lit environments. Studies have shown that projections in bright rooms can shift perception from an appearance of self-luminosity to one of being illuminated. This advancement holds significant promise for applications that require visual naturalness, such as product design. Nonetheless, the influence of projected content on perception and the underlying mechanisms of perceptual color transitions in projection targets remain unclear. In this study, we found that the presence or absence of patterns in the projected content affects the luminosity threshold at which the projection target is perceived as self-luminous. Previous research in perception has suggested that the visual system relies on intrinsic criteria to determine whether an object is self-luminous. However, our results revealed that in projection mapping, the internal reference for color perception, developed through observations of colors in daily life, does not always apply. These results indicate the existence of perceptual phenomena unique to projection mapping. This insight is crucial for product design, as it aims to achieve representations that closely resemble the appearance of real-world objects.

KEYWORDS

augmented reality, projection mapping, perception, color vision, luminosity threshold

1 Introduction

Projection mapping (PM) is a technology that alters the appearance of objects by projecting images onto physical surfaces. This is achieved by changing the apparent reflectance properties of real-world surfaces. Raskar et al. proposed and demonstrated a fundamental framework in which the radiance pattern of a real surface under white illumination is reproduced by projecting a similar texture pattern onto a white object (Raskar et al., 2001). Since then, research on PM has focused on how closely values measured by cameras or radiometers match the target values, leading to advances in color compensation techniques (Bimber et al., 2008; Iwai, 2024). However, regardless of how accurately colors are displayed, observers typically do not perceive the change as a modification of the surface's reflectance properties or as a material-derived color change. There are numerous application domains where it is essential to suppress the typical visual artifacts of PM and to ensure that color changes are perceived as naturally originating from the material itself. These domains include industrial design (Cascini et al., 2020; Marner et al., 2014; Menk et al., 2011; Takezawa et al., 2019; Yoshida et al., 2025), remote communication (Iwai et al., 2018; Pejsa et al., 2016; Raskar et al., 1998), remote color reproduction of artworks (Bimber et al., 2005; Schmidt et al., 2019; Bandyopadhyay et al., 2001; Flagg and Rehg, 2006; Rivers et al., 2012), and makeup (Bermano et al., 2017; Siegl et al., 2017; Tsurumi et al., 2023; Peng et al., 2025), all extensively investigated. However, due to the occurrence of the visual perception unique to PM, current PM technology cannot accurately represent or reproduce the perceived material properties of real objects, thus limiting its application in these fields. A major drawback contributing to this perceptual inconsistency is that PM is strictly limited to dark environments. When PM is performed in a darkroom environment, only the PM target is brightly illuminated while the surroundings remain dark, resulting in the target appearing unnaturally bright (RadonjiÄ et al., 2011; Morimoto et al., 2021).

In recent years, this significant limitation of PM being restricted to darkrooms has been addressed through proposals to replicate the environmental lighting using projectors to illuminate areas other than the projection target (Amano and Kubo, 2022; Yasui et al., 2024; Takeuchi et al., 2024). Takeuchi et al. indicated that PM under environmental lighting suppresses its unique visual perception by shifting the target's perceived color appearance from aperture color mode to surface color mode (Takeuchi et al., 2024; Katz, 1935). However, although it has been suggested that the degree of mode transition depends on the projected texture, the mechanism behind this remains unclear. It has been pointed out that the participants' judgments may have been biased by rich contextual information, specifically their awareness that the object was being projection-mapped. In particular, it is unclear how the projected texture itself and its brightness affect the perceptual color mode transition in PM objects.

We focus on the texture pattern of the projection target as factors contributing to projection appearance in PM. This study aims to investigate how the projected content influences perceptual mode switching. A common approach to studying color appearance is to measure the transition luminance between surface color mode and aperture color mode, known as the luminosity threshold. Previous studies have suggested that the threshold is determined by the maximum luminance estimated from the stimulus periphery, although these investigations were limited to uniformly colored targets (Ullman, 1976; Bonato and Gilchrist, 1994; Uchikawa et al., 2001; Morimoto et al., 2021). In this study, we investigate whether the previously reported findings on the luminosity threshold apply in the context of PM in an illuminated room. We also investigate if there is a unique luminosity threshold for PM. Previous studies have demonstrated pronounced shifts from aperture color mode to surface color mode conducted under well-lit conditions, implying that perceptual mode judgments rely on the peripheral luminance information surrounding the projection target (Takeuchi et al., 2024). When the visual system determines whether an object is perceived as aperture color mode based on its surroundings, the luminosity threshold should change depending on the brightness level of the surroundings. As previous studies have shown, it can also be assumed that stimuli with high purity will appear brighter when the target has a uniform color (Nayatani et al., 1991; Donofrio, 2011). Furthermore, since it has also been reported that the degree of this transition varies depending on the texture projected onto the target, we expect that the texture and color purity of the content also influence the luminosity threshold determination. Typically, ambient illumination in everyday environments originates from simple light sources with relatively uniform spatial luminance distributions. Consequently, when uniform-colored content is projected onto an object, observers may tend to interpret it as a change in the color of the spotlight illuminating it. For uneven texture, increasing its overall luminance creates localized bright pixels within the pattern, resulting in high local contrast. We propose that this internal contrast acts as a key cue for perceiving an object as self-luminous. Conversely, in the absence of a texture, as with a uniform projection, this contrast-based cue is unavailable. Therefore, we expect observers to rely on other colorimetric properties to judge brightness, such as stimulus purity, as has been suggested in previous luminosity threshold experiments. Based on these considerations, we formulated the following hypotheses:

Hypothesis 1: In a real environment with PM, the luminosity threshold is determined by the object's surroundings.

Hypothesis 2: Stimuli with higher color purity are perceived as brighter than those with the same physical luminance in a PM environment.

Hypothesis 3: Luminosity thresholds are lower for uneven texture compared to uniform texture.

Hypothesis 4: As the contrast of the texture increases, the luminosity threshold also rises.

To test this hypothesis, we conducted a human psychophysical experiment to determine the luminosity threshold at which the color appearance of an object transitions between the two color modes. In the experiment, the scene was selectively illuminated by projectors while excluding the projection target itself. The experiment aimed to determine whether the luminosity thresholds vary for different types of textures projected onto objects under different environmental lighting conditions with varying intensity.

2 Methods

2.1 Apparatus

The experimental setup is shown in Figure 1. This experiment was conducted in a room illuminated using the method proposed by the previous study (Takeuchi et al., 2024). We built a typical living room by setting up a sofa, a desk, and other furniture in a laboratory space measuring 2.8 × 2.2 m. Additionally, we placed a 200 mm tall white statue on the desk as the projection target. Using a spectroradiometer (Topcon SR-LEDW) and a standard white reference plate (Evers Corporation EVER-WHITE No. 9582), we measured the reflectance of the object's surface. The reflectance values measured within the visible spectrum were averaged, resulting in a mean value of 0.56. We installed a total of seven

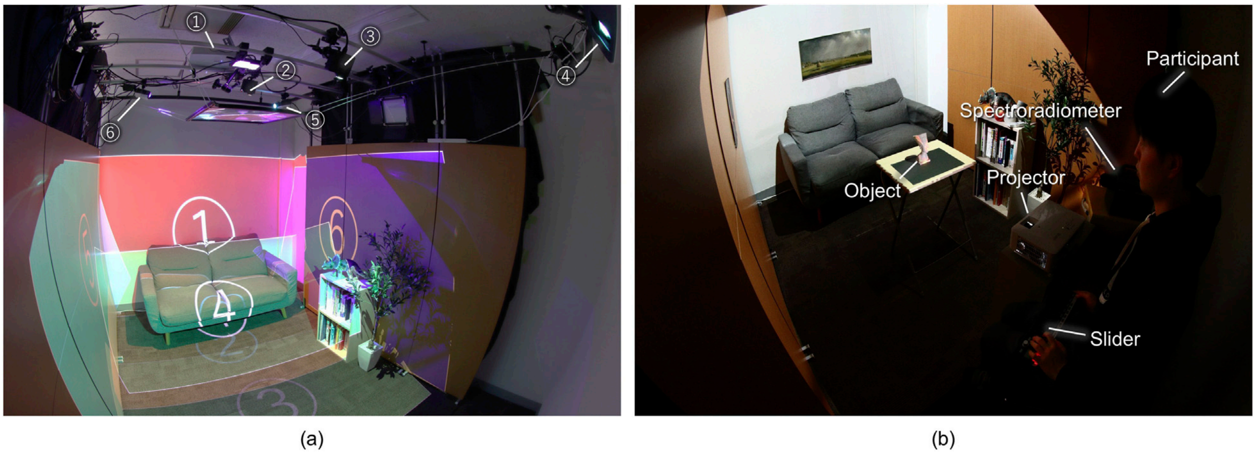

FIGURE 1
Experimental setup. **(a)** Projector arrangement (© 2024 IEEE). **(b)** Arrangement of the participant and the projected object.

projectors: six as luminaire projectors and one as a texture projector. Luminaire projectors consist of five standard projectors and one custom-made large-aperture projector. Among the standard projectors, two (Optoma ML1050ST + S1J) illuminated the side walls, one (Acer H6517ST) illuminated the front wall, and two (RICOH PJ WXC1110) illuminated the floor. The large-aperture projector was positioned near the projection object to minimize hard shadows, anticipating interaction with the target. In this experiment, participants did not directly touch the projection target. The large-aperture projector, consisting of an LCD display (OSEE T7) and a 500 × 500 mm Fresnel lens (SIGMAKOKI FRLN-500S-250P), was installed to illuminate the desk. Standard projector (BenQ TH685) was also used as the texture projector onto the surface of the target. All projectors were controlled via a PC (CPU: AMD Ryzen 9 3900 X 12-Core Processor, RAM: 64 GB) and mounted on the ceiling except the texture projector (Height: 2.3 m).

2.2 Luminosity thresholds experiment

2.2.1 Participants

The participants were four Japanese (two males and two females, aged 23–25 years). No monetary compensation was provided. The participants were unaware of the purpose of the experiment. All participants had corrected vision. Several breaks were given to the participants during the experiment. The study was approved by the Research Ethics Committee of Graduate School of Engineering Science at The University of Osaka (approval number; R5-6).

2.2.2 Stimuli

Two environmental lighting conditions of different intensity (mean luminance 1.0 and 6.0 cd/m^2) were employed to evaluate their impact on determining the luminosity threshold. We hypothesized that these two lighting levels would produce significantly different luminosity thresholds. To verify these lighting distributions, the luminance at arbitrary points in the room was measured. Luminance values were obtained not only around the projection target object but also for the entire room visible within the field of view. A segmentation model (Kirillov et al., 2023) was used to divide the room's appearance into regions, and measurement points were evenly extracted from within each region. The average chromaticity was (u', v') = (0.23, 0.51) for Condition 1 and (u', v') = (0.22, 0.50) for Condition 2, both corresponding to a color temperature of approximately 4200 K.

For projection textures, we employed eight texture stimuli (Figure 2). (a)–(d) were uneven textures exhibiting varied local contrast and luminance distributions, whereas textures (e)–(h) were uniform textures of constant luminance, three of which were chromatic (chosen to broadly span the hue circle) and one achromatic (neutral gray). Each texture was projected onto the target object at a resolution of approximately 130 × 290 pixels, resulting in about 29,000 pixels on its surface.

2.2.3 Procedure

Participants first completed a brief dark adaptation period, during which the experimental procedure was explained to them.

Participants sat on a stool, fixated on the designated object, and performed evaluations using the method of adjustment. Their task was to use a luminance-adjustable slider (Worlde EasyControl.9) to adjust only the luminance of the projected texture to the level where it transitioned from the surface color mode to the aperture color mode. The slider operated on a linear scale based on absolute values, and its range was pre-calibrated using a white projection. Considering the ambiguity in judging the transition between modes reported in previous studies (Speigle and Brainard, 1996; Uchikawa et al., 2001), we instructed participants as follows: "Your task is to adjust the luminance of the object on the desk so that it appears to be at the midpoint between the upper limit of the surface color mode and the lower limit of the aperture color mode." The upper limit of the surface color mode and the lower limit of the aperture color mode were explained as the boundaries where the object on the desk appears entirely as an illuminated surface and entirely as a light source, respectively. This instruction was designed to provide a consistent criterion for the transition point, as there can be a range of luminance values where both modes coexist.

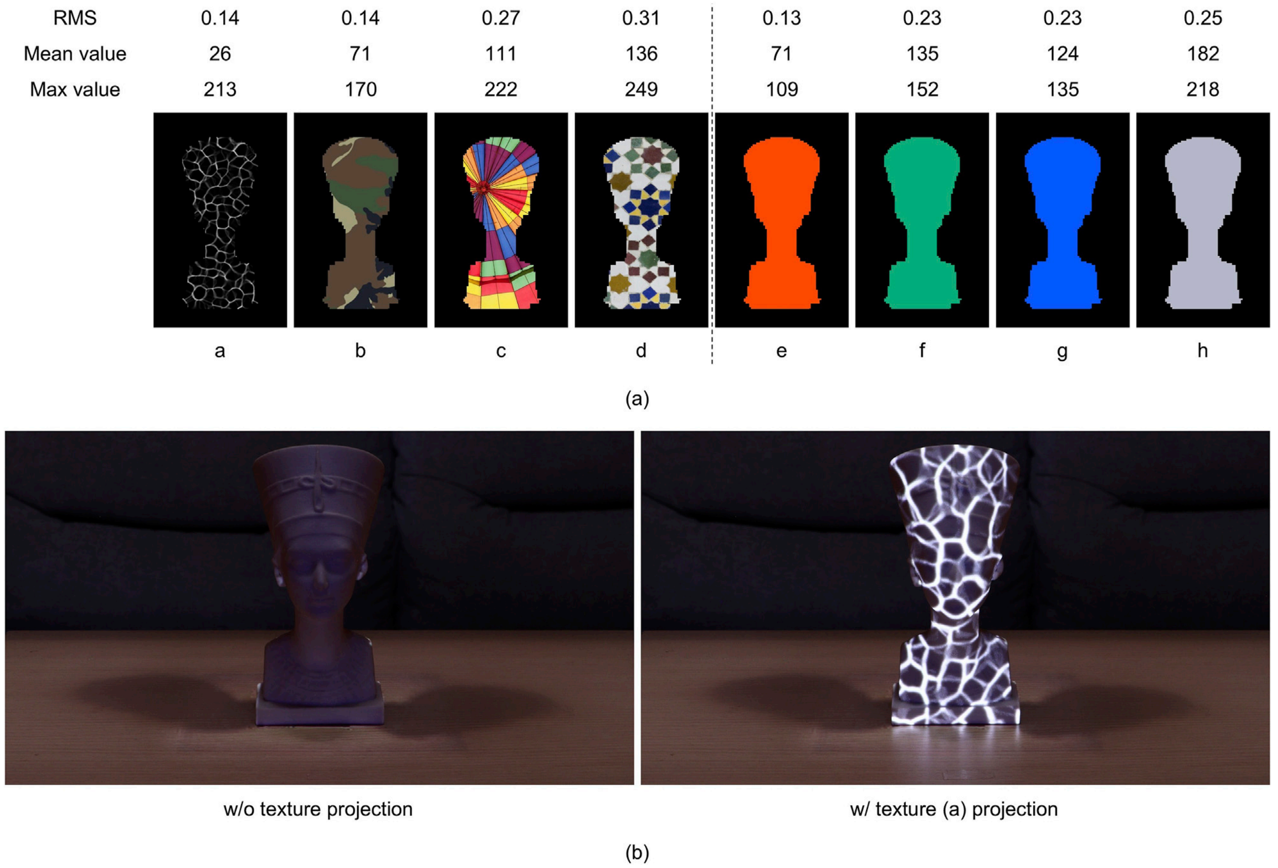

FIGURE 2
Textures used in the experiment. **(a)** Statistical properties (RMS contrast, mean value, and maximum value) and the projected images of the eight prepared textures. **(b)** The white statue used as a projection target (left) and an example of texture projection (right) (© 2024 IEEE). The system developed by Takeuchi et al. selectively illuminates the background, leaving the statue dark.

Participants notified the experimenter when the luminance adjustment was complete. The experimenter then recorded the luminance of the face area of the statue using the spectroradiometer. The spectroradiometer was positioned to ensure that the measurement circle reached its largest size without overhanging the face area, and the area-weighted average was used as the result.

For each texture, the measurements were repeated three times using three different initial values: “brightest,” corresponding to the brightness at the maximum slider position; “darkest,” corresponding to the brightness at the minimum slider position; and “random,” which indicated a value between the brightest and darkest settings. In total, each participant completed a total of 48 trials, consisting of 2 conditions × 8 textures × 3 repetitions. To control for potential order effects, the presentation order of the two conditions was counterbalanced across participants. Within each condition, the presentation order of the eight textures was randomized for each participant.

3 Results

The measurement result is shown in Figure 3. The graphs show the mean values of the luminosity threshold set by the participants. Even under the same conditions for the same participant, hysteresis effects were observed, with differences in measurement values depending on the initial values. Therefore, the average value was adopted to offset the effects of the initial values. Given the high correlation between the two lighting conditions ($r = 0.85$), the data were averaged to better illustrate the primary focus of this study: the differences in luminosity threshold due to texture. Individual data for each participant can be found in the Supplementary Material. First, to examine differences in the adjusted luminosity between the two lighting conditions, we used a linear mixed-effects model, with the log-scaled luminosity thresholds as the dependent variable to normalize the positively skewed distribution of the raw data. The model revealed a significant main effect of condition on the luminosity threshold. Specifically, the thresholds were significantly higher in the intervention condition (condition 2) compared to the reference condition by an average of 0.47 (95% CI, 0.18 to 0.76; $p < .01$). However, there was no significant interaction effect between condition and stimulus, indicating that the effect of the condition on the luminosity threshold was consistent across all stimulus types. This result is consistent with previous psychophysical studies reporting that peripheral luminance information is referenced when determining luminosity thresholds. Therefore, Hypothesis 1 is supported. Regarding the luminosity thresholds for uniform textures, texture (h) tended to have the higher luminosity threshold compared to the

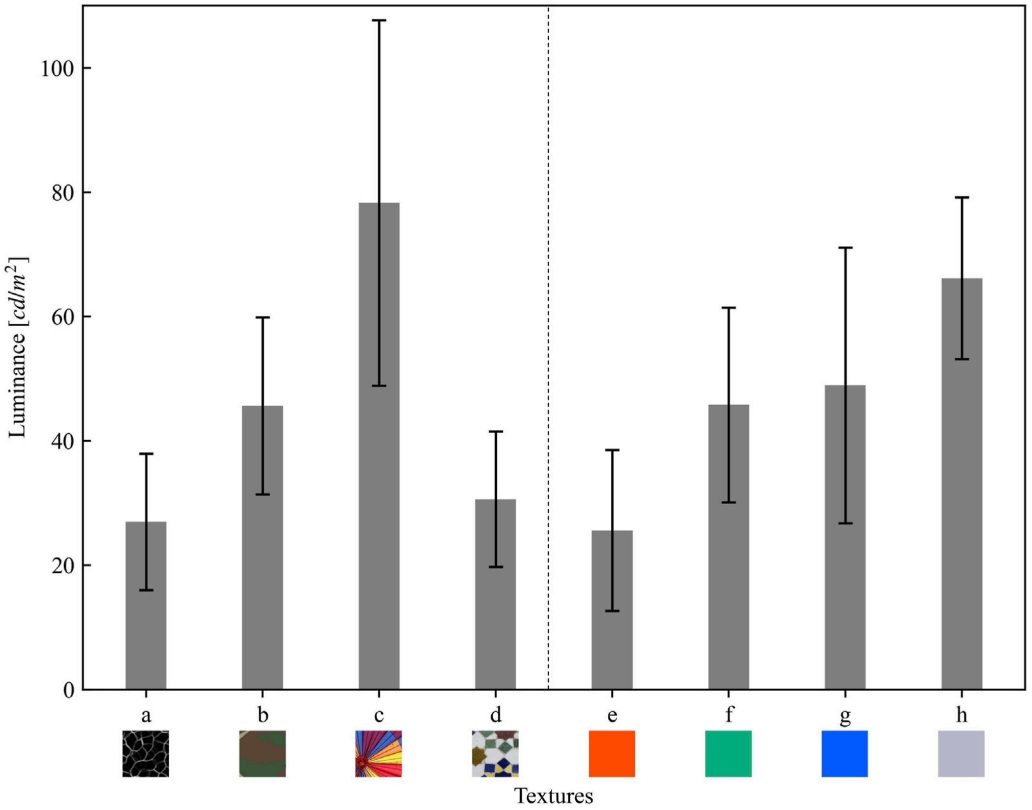

FIGURE 3
Experimental result. Mean luminosity thresholds for each texture.

other uniform textures. Although this difference was not statistically significant, the trend is consistent with previously reported luminosity threshold loci (Uchikawa et al., 2001; Morimoto et al., 2021). Therefore, Hypothesis 2 is partly supported. Regarding the effect of texture type, we did not find a conclusive relationship between texture uniformity and luminosity thresholds. Therefore, our Hypothesis 3 was not supported. This result suggests that a simple classification of uniform versus uneven is not sufficient to explain the perception of self-luminosity. Interestingly, this finding from our quantitative data contrasts with some participants' subjective reports, which indicated that uneven textures were consistently perceived as being projected regardless of brightness. This discrepancy between the quantitative thresholds and qualitative reports warrants further investigation. Finally, we analyzed the relationship between the RMS contrast of uneven textures and their luminosity thresholds. However, we found no statistically significant correlation between these two variables. For instance, while some textures with higher RMS contrast showed higher thresholds, texture (d) represented a clear exception with a relatively low threshold despite its RMS contrast. Therefore, our results do not support the Hypothesis 4 that RMS contrast is a primary determinant of the luminosity threshold for this phenomenon.

4 Discussion

We investigated the luminosity thresholds in PM. For uniform textures, the highly purity texture (e), (f), and (g) were measured as having lower luminance values compared to texture (h). This suggests they were perceived as self-luminous at a low brightness, making it difficult to see them as surface colors. This can be attributed to the Helmholtz-Kohlrausch effect, which states that highly saturated stimuli appear brighter than less saturated ones at the same luminance. This phenomenon has been reported under various visual conditions (Nayatani et al., 1991; Donofrio, 2011). Our experiment also observed this effect. In contrast, uneven textures containing highly saturated colors did not show a clear trend in luminosity threshold. The participants' introspective reports indicated that uneven textures were perceived as being projected regardless of brightness, and the measured luminosity thresholds were not higher than those for uniform textures. This suggests that the presence of patterns enhances the projection appearance, leading to the perception of self-luminosity even at lower luminance levels. In other words, objects that typically do not emit light, such as uneven textures, are more likely to be perceived as self-luminous at low luminance. In contrast, objects that resemble familiar light sources, like uniform, spotlight-like textures tend to be perceived as self-luminous only at higher luminance. This tendency may influence color appearance in PM and contribute to the unique perceptual phenomena associated with PM. Therefore, our findings suggest that the luminosity threshold for judging self-luminosity may not be determined solely by intrinsic visual system criteria. Instead, it could also be influenced by contextual information, such as the presence of projected content and patterns that are not typically associated with self-luminous objects in everyday experience.

In the experiment, the perceptual color mode may have been unfamiliar to the participants, and it is possible that they responded based on their sense of ”projection appearance” rather than strictly as color appearance mode. Thus, instead of asking about the mode, it may have been more direct and comprehensible for participants to evaluate material properties such as glossiness, which are more familiar. Alternatively, asking participants to name the perceived color could also be effective. For example, it is known that brown may be perceived in surface color mode, whereas the same stimulus may appear orange in aperture color mode (Uchikawa et al., 1989). Utilizing this could help identify the perceptual mode. Additionally, although luminance was measured with the spectroradiometer, it only captured the average luminance of the entire visual field, which may not have matched the specific region the participant was fixating on. It was not possible to determine which part of the projection target the participant was focusing on when setting the luminosity threshold; thus, future studies should consider using eye tracking to investigate this aspect. The primary limitation of this study is the small sample size (N = 4), which limits its statistical power. Consequently, this work should be regarded as a pilot study exploring perceptual tendencies in PM environments. The contribution of this study lies not in the generalizability of its conclusions, but in its pioneering attempt to explore the perceptual characteristics of projected content in PM, which is a previously unexamined area of inquiry. To the best of our knowledge, this is the first study to undertake such an exploration. Although our results indicated trends whereby color purity (H2) and the presence of texture (H3) influence luminosity thresholds, these effects did not attain statistical significance. To confirm the robustness of these observations and derive more generalizable conclusions, future research with larger samples is essential.

This study revealed that intrinsic luminosity threshold criteria for color appearance, established in real-world viewing, are not directly applicable to the context of PM. This discrepancy is a critical consideration for design support aimed at achieving projected representations that are faithful to real-world object appearance. To bridge this perceptual gap, future work should systematically investigate other visual cues, such as surface texture, which was a limitation in this study. Ultimately, overcoming such perceptual discrepancies is essential to advance PM from a novel display technology to a true substitute for environmental lighting, thereby realizing more realistic and immersive visual experiences.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Institutional review board (IRB) of the Graduate School of Engineering Science at the University of Osaka. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MT: Visualization, Formal Analysis, Project administration, Conceptualization, Writing – review and editing, Data curation, Methodology, Software, Investigation, Writing – original draft. KK: Writing – review and editing, Validation. DI: Conceptualization, Funding acquisition, Resources, Writing – review and editing, Supervision.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2025.1649901/full#supplementary-material

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