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Increased color preference through the introduction of luminance noise in chromatic stimuli

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Humans exhibit consistent color preferences that are often described as a curvilinear pattern across hues. The recent literature posits that color preference is linked to the preference for objects or other entities associated with those colors. However, many studies examine this preference using isoluminant colors, which don't reflect the natural viewing experience typically influenced by different light intensities. The inclusion of random luminance levels (luminance noise) in chromatic stimuli may provide an initial step towards assessing color preference as it is presented in the real world. Employing mosaic stimuli, this study aimed to evaluate the influence of luminance noise on human color preference. Thirty normal trichromats engaged in a two-alternative forced-choice paradigm, indicating their color preferences between presented pairs. The chromatic stimuli included saturated versions of 8 standard hues, presented in mosaics with varying diameters under different luminance noise conditions. Results indicated that the inclusion of luminance noise increased color preference across all hues, specifically under the high luminance noise range, while the curvilinear pattern remained unchanged. Finally, women exhibit a greater sensitivity to the presence of luminance noise than men, potentially due to differences between men and women in aesthetic evaluation strategies.

Human color preferences display consistent patterns[1]. Although factors such as gender, age, and culture can influence these preferences[2], color preferences generally follow a curvilinear "S" pattern across hues, with a peak at blue and a trough between yellow and green[3,4].

Various theories have been proposed to explain why humans prefer certain colors over others, among which the Ecological Valence Theory (EVT) stands out. According to EVT, color preference can be explained by the preference for objects, entities or abstract concepts associated with those colors[5]. Indeed, subsequent evidence has shown strong correlations between color preference and the preference for colored objects with those same colors[6–8], although it does not perform well across different cultures, especially non-Western ones. For example, while it aligned well with data from England and US[8,9], it explained Japanese[9] and Arabic preferences[10] much less effectively, and it failed to account for Himba preferences[11].

While this theory takes into account how colors are evaluated in objects in the natural environment, most studies have examined color preference by presenting chromatic stimuli under optimal viewing conditions (for recent examples, see[10,12,13]), often using isoluminant colors, which typically do not reflect real-world conditions outside the laboratory. In the environment, colors are perceived under different light intensities, irregularly distributed on the surfaces of objects[14,15]. Hence, although the irregular distribution of luminance is not the only factor that differentiates these artificial stimuli from their presentation in the real world, incorporating randomly arranged luminance values (luminance noise) into chromatic stimuli may provide an initial step towards evaluating color preference in a more ecologically valid manner.

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In perception studies, noise is generally conceived as the unpredictability of some aspect of the stimulus, and the inclusion of noise has been widely used to assess vision-related tasks (e.g., spatial, luminance, and chromatic noise)[16]. Mosaic stimuli can be employed to manipulate this inclusion of noise, as seen in pseudoisochromatic stimuli[17]. These stimuli present different patches of various sizes (spatial noise) in which color and luminance can be manipulated randomly or non-randomly (e.g., see examples of previous works by our group manipulating luminance noise[18,19], and chromatic noise[20,21]). Using this type of arrangement, we can include luminance noise in chromatic stimuli without necessarily adding a real-world context (e.g., presenting colors linked to real objects). Based on this, the present study aimed to evaluate the influence of the inclusion of luminance noise on human color preference using mosaic chromatic stimuli.

Methods

Subjects

Thirty normal trichromats subjects (15 women, 15 men, aged 25.1 ± 4.1 years) with normal or corrected-to-normal vision were recruited for convenience. All participants are Brazilians from the northern region of the country, Amazon region. Visual acuity was evaluated using the Early Treatment Diabetic Retinopathy Study (ETDRS) Letters chart, and the screening for congenital color vision deficiencies was assessed using the Ishihara 36 Plates Color test. Written Informed Consent was obtained from all participants, and the study protocol received approval from the Ethics Committee of the Center for Tropical Medicine at the Federal University of Pará, Brazil (report #5.779.610/2022). All methods were performed in accordance with relevant guidelines and regulations.

Stimuli

The color preference test was conducted using the ViSaGe system (CRS) with a CRT monitor (14 bits of color resolution per gun; resolution: 1600 × 1200 pixels, refresh rate: 75 Hz, model Diamond Pro 2070SB 22", Mitsubishi, Australia). A gamma correction procedure was done in the display using a chromameter and the software vsgDesktop (ColorCal II, CRS). The chromatic stimuli presented consisted of saturated versions of 8 hues from the Berkeley Color Project (BCP-32)[5]. The hue set comprised: red (R), yellow (Y), chartreuse (H), green (G), cyan (C), blue (B) and purple (P) (Fig. 1a). Each hue was presented in mosaics formed by circles of varying diameters under three different luminance noise conditions: 20 cd/m^2 (no noise), 15–25 cd/m^2 (10 cd/m^2 range), and 10–30 cd/m^2 (20 cd/m^2 range) (Fig. 1b). The mean luminance was maintained at 20 cd/m^2 for all presented conditions. To prevent preference from being influenced by the arrangement of circles, the same arrangement was maintained for all presented stimuli.

Procedure

Chromatic stimuli were presented to participants in pairs, side by side, under different luminance noise conditions in a two-alternative forced-choice paradigm (2-AFC). All possible combinations of stimuli were presented twice, with only a modification in their order (8 hues, 3 luminance noise conditions, 552 evaluations). Participants were instructed to indicate their preference between the two presented colors. To avoid any bias in participant choice, no additional instructions were given. The pairs were displayed for 3 s, followed by a fixation cross that remained on the screen until the participant's response was recorded. Figure 1c provides a schematic summary of this procedure. All pairs were presented in a random order, and the proportion in which a specific color was chosen by an individual, when presented, served as the preference index. Participants were situated at a fixed distance of 2 m from the screen in a climate-controlled, darkened environment, with the only light source being the monitor used in the test. Responses for both tests were recorded by the examiner using a four-button response box model CT6 (CRS) (Fig. 1d).

Data analysis

To assess the impact of luminance noise condition on preference indices for each hue, we employed Linear Mixed-Effects Models (LMMs). We used a main model incorporating the following fixed effects: luminance noise condition, hue, participant gender, and all possible two-way interactions among these variables. To assess the consistency of the luminance noise effect on preference across hues, we used separate LMMs for each hue, considering only luminance noise condition as a fixed effect. Additionally, similar gender-specific models were employed to explore gender-related differences. For all models, *post-hoc* analyses were then performed through pairwise comparisons defined by linear contrasts, and the Tukey method was applied to control for multiple testing. Additionally, subject ID was included as a random effect to account for the repeated data structure. The *F*-statistic and *p*-values for each variable in the models were estimated using Type-III ANOVA. Visual inspection of residuals, along with the Shapiro–Wilk normality test and a Bartlett test of homogeneity of variance, was employed to assess model assumptions.

The analyses and graphical representations were conducted using *R* software version 4.3.2[22], along with the following packages: *lme4*[23] for constructing LMMs; *lmertest*[24] for estimating *p*-values based on the Satterthwaite approximation; *performance*[25] for visual and statistical inspection of LMMs residuals; and *ggplot2*[26] for data visualization. The significance level was set at $\alpha = 0.05$.

Results

From our main model (Table 1), we found that the inclusion of luminance noise had a significant effect on the mean preference indices ($F_{(2,686)} = 8.79$; $p < 0.001$, Fig. 2a). We also found a significant effect of hue ($F_{(7,686)} = 52.92$; $p < 0.001$), as well as an interaction between hue and participant gender ($F_{(7,686)} = 4.51$; $p < 0.001$). The well-known "S" shape of color preference across hues was replicated in our Brazilian sample.

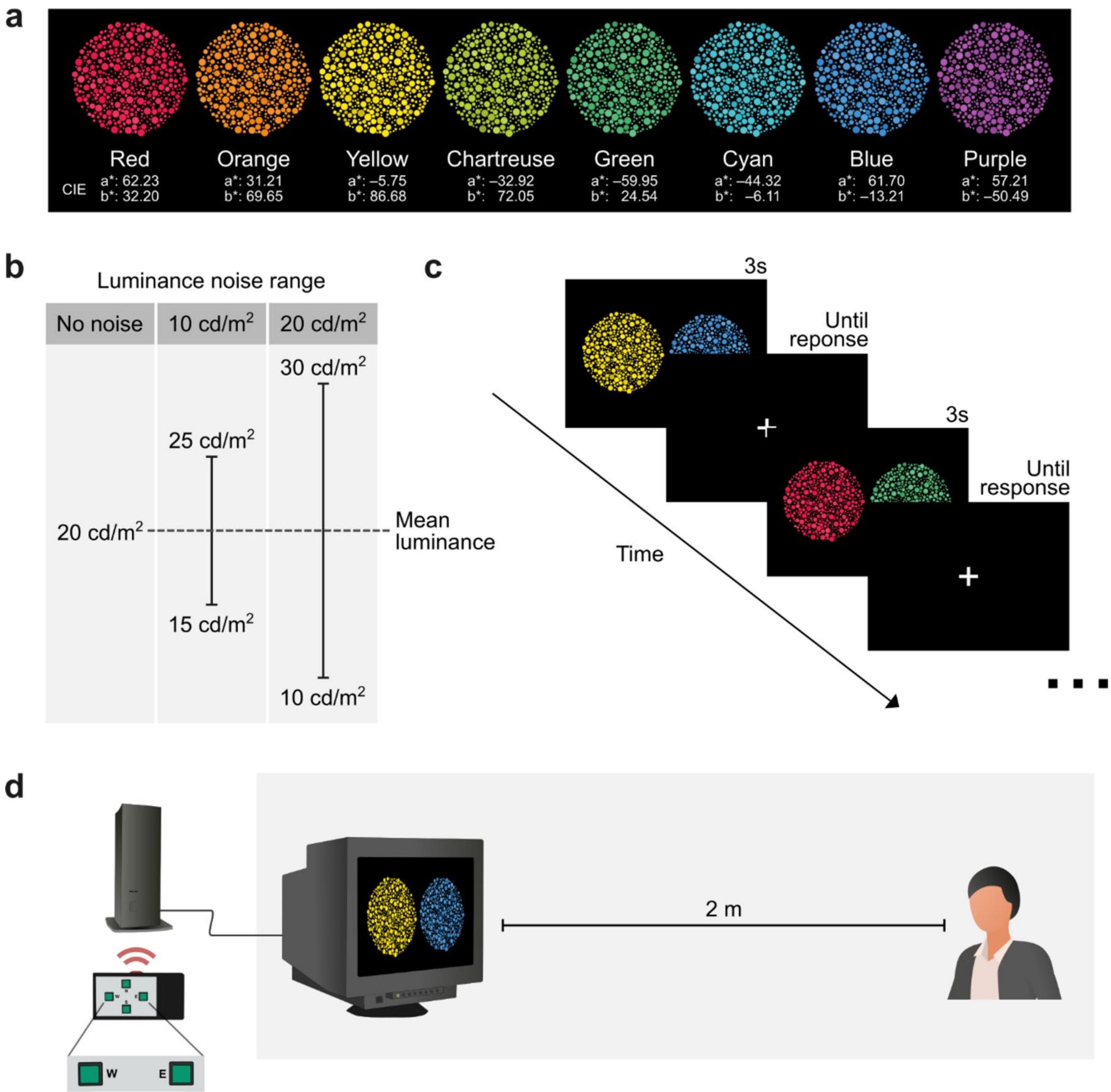

Figure 1. Chromatic stimuli and experimental procedure. In (**a**), examples of mosaics are shown for each of the hues used. Below each mosaic are the a*b* coordinates in the CIELAB color space. L* values are omitted as they are manipulated through luminance noise. In (**b**), a schematic of the ranges for each luminance noise condition is presented. cd/m^2: candela per square meter. In (**c**), the procedure for presenting chromatic stimuli is outlined. In (**d**), the apparatus used in the experiment for stimulus presentation (CRT monitor + ViSaGe System) and recording participant responses (four-button response box model CT6) is depicted.

Fixed effect	Df	*F*	*p*
Luminance noise condition	2	8.79	< 0.001
Hue	7	52.92	< 0.001
Gender	1	< 0.001	0.999
Luminance noise condition: Hue	14	0.09	0.999
Luminance noise condition: Gender	2	2.14	0.118
Hue: Gender	7	4.51	< 0.001

Table 1. Results from the main Linear Mixed-Effects Model (LMM) for the effect of luminance noise condition, hue, and gender on mean color preference *F*-statistic and *p*-values were estimated using Type-III ANOVA

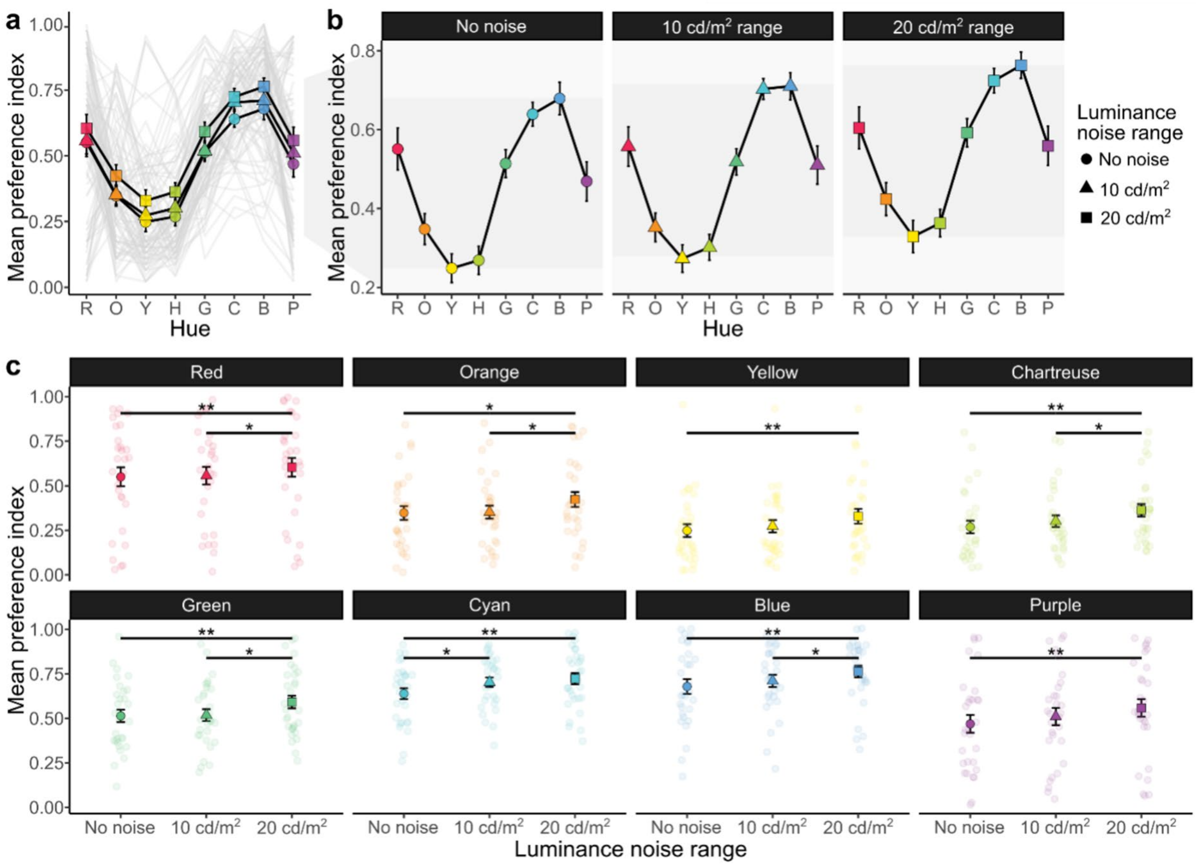

Figure 2. Effect of the inclusion of luminance noise on the mean preference index by hue. In (**a**), mean preference indices (± standard error) are presented for each hue under three luminance noise conditions. Individual data are depicted with gray lines in the background. In (**b**), subplots display the same preference indices for each hue under the three noise conditions separately. The boundaries of the dark gray rectangles in the background of the subplots denote the minimum and maximum preference for each condition. In (**c**), mean preference indices are presented as a function of luminance noise conditions for each hue separately. Dots represent single data points. Hues were encoded as follows: red (R), yellow (Y), chartreuse (H), green (G), cyan (C), blue (B) and purple (P). cd/m^2: candela per square meter. *$p<0.05$, **$p<0.01$.

Overall, irrespective of hue, Tukey's *post-hoc* test revealed a significant increase in preference in the presence of the highest luminance noise range used (20 cd/m^2) compared to the no noise condition ($p<0.001$) and the intermediate range noise condition (10 cd/m^2; $p=0.016$). No significant difference was found between the no noise and intermediate noise condition ($p=0.375$; Fig. 2b).

To confirm the consistency of this effect across hues, we tested each hue separately (Fig. 2c). The inclusion of luminance noise had a significant effect on color preference for all eight hues: red ($F_{(2,58)}=5.68$; $p=0.006$), orange ($F_{(2,58)}=5.39$; $p=0.007$), yellow ($F_{(2,58)}=5.94$; $p=0.004$), chartreuse ($F_{(2,58)}=7.42$; $p=0.001$), green ($F_{(2,58)}=6.16$; $p=0.004$), cyan ($F_{(2,58)}=6.91$; $p=0.002$), blue ($F_{(2,58)}=8.17$; $p<0.001$) and purple ($F_{(2,58)}=8.97$; $p<0.001$). Overall, consistent with our main model, Tukey's *post-hoc* test revealed significant differences between the no noise condition and the highest range noise condition for all hues: red ($p=0.009$), orange ($p=0.013$), yellow ($p=0.004$), chartreuse ($p=0.001$), green ($p=0.008$), cyan ($p=0.002$), blue ($p<0.001$), and purple ($p<0.001$). Additionally, we found significant differences between the intermediate noise range condition and the highest noise range condition for the following hues: red ($p=0.023$), orange ($p=0.021$), chartreuse ($p=0.042$), green ($p=0.012$), and blue ($p=0.038$), but not for yellow ($p=0.059$), cyan ($p=0.652$), and purple ($p=0.066$). A significant difference between the no noise condition and the intermediate noise range condition was found only for cyan ($p=0.025$).

We did not find a significant effect of the interaction between hue and luminance noise condition on mean preference ($F_{(14,686)}=0.09$; $p=0.99$), indicating that preference increased in the presence of higher range of noise, but there was no significant change in the shape of the preference curve. In other words, hues that were preferred under one noise condition were also preferred under another, as visualized in Fig. 1b.

The interaction between hue and participant gender ($F_{(7,686)}=4.51$; $p<0.001$) indicated that, regardless of luminance noise condition, there was a significant difference in color preference between men and women. Tukey's *post-hoc* test revealed that this gender-related difference is limited to the following hues: red ($p=0.024$), chartreuse ($p=0.042$), blue ($p=0.018$), and purple ($p=0.003$). Generally, men preferred red, blue, and purple hues more, whereas women favored chartreuse.

Although from our main model, no significant effect was found for the interaction of participant gender and luminance noise condition ($F_{(7,686)} = 2.14$; $p = 0.118$), separate models by gender revealed that the presence of luminance noise significantly increased the mean preference for women ($F_{(2,357)} = 6.28$; $p = 0.002$) in the presence of the 20 cd/m^2 range (Tukey's *post-hoc* test: no noise *vs*. 20 cd/m^2 range, $p = 0.002$; 10 cd/m^2 vs. 20 cd/m^2 range, $p = 0.039$), which was not observed for men ($F_{(2,357)} = 0.77$; $p = 0.462$). This gender difference in the effect of luminance noise on color preference can be visualized in Fig. 3a.

This difference is further confirmed through multiple comparisons between the mean gender preferences in each of the luminance noise conditions (Fig. 3b). Similarly to what was observed in our main model, under the conditions of no noise and 10 cd/m^2 range, men exhibited a more pronounced preference for red (no noise: $p = 0.008$; 10 cd/m^2: $p = 0.021$), blue (no noise: $p = 0.006$; 10 cd/m^2: $p = 0.016$), and purple (no noise: $p = 0.001$; 10 cd/m^2: $p = 0.004$). However, in the presence of a luminance noise condition with a range of 20 cd/m2, women showed a higher preference for orange ($p = 0.045$), yellow ($p = 0.012$), chartreuse ($p = 0.006$), and cyan ($p = 0.019$) compared to men. The difference in mean preference between genders was not significant for other hues; that is, the presence of noise equalized the preference for red, blue, and purple across genders, indicating an overall increase in preference for women in the presence of a greater range of luminance noise (Fig. 3b).

Discussion

In this study, we investigated the impact of introducing luminance noise to chromatic stimuli on color preferences in a Brazilian sample. Our findings suggest that the inclusion of luminance noise, without mean luminance change, increases color preference across all hues, particularly under conditions of high noise range. However, the frequently reported curvilinear pattern[4] remained unchanged.

The Ecological Valence Theory (EVT), proposed by Palmer and Schloss[5], posits that color preferences are influenced by individuals' overall liking or disliking of environmental objects or other entities associated with those same colors. Subsequent evidence has shown some success of EVT in explaining human color preference[5–8,11], although cross-cultural limitations should be taken into account[9–11]. However, stimuli commonly used in studies investigating color preference employ isoluminant chromatic stimuli, i.e., color patches with uniform luminance distributed across their surface, for recent examples, see:[10,12,13]. In real-world settings, colors

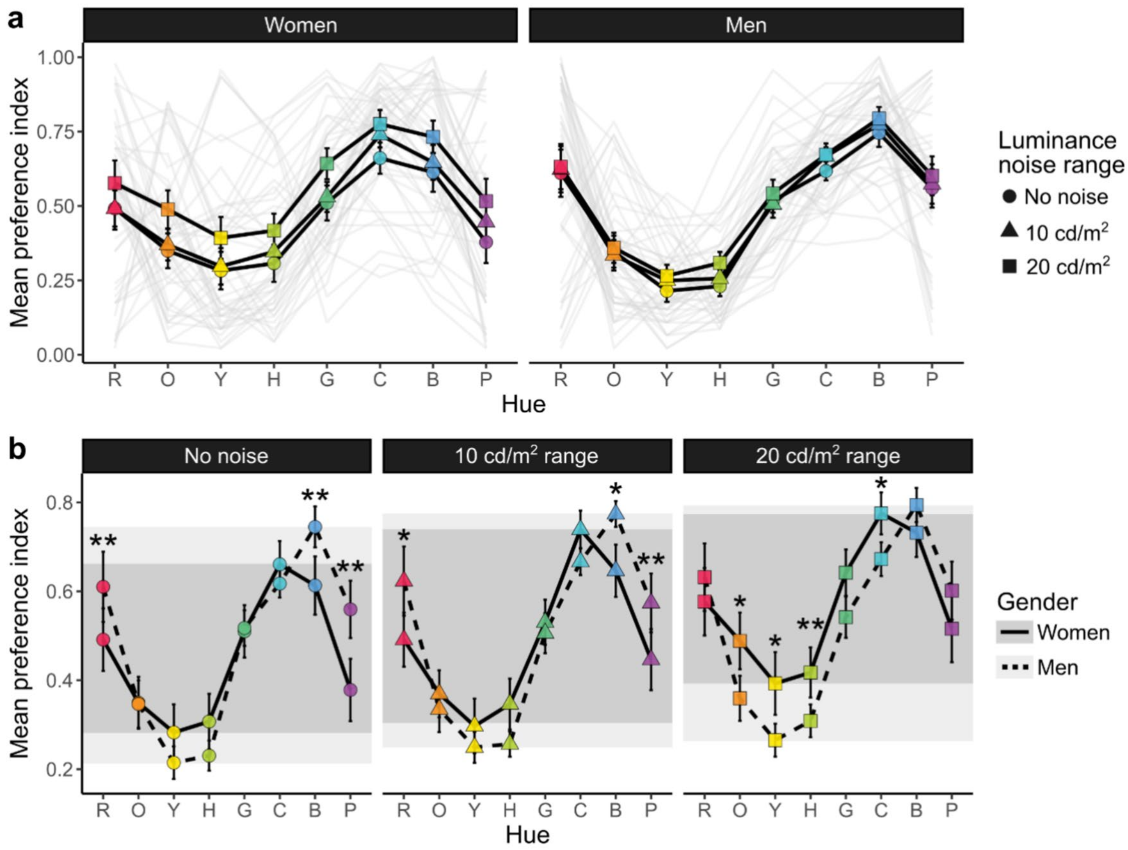

Figure 3. Gender differences in color preference across luminance noise conditions. In (**a**), mean preference indices (± standard error) for women and men are presented for each hue under three luminance noise conditions. Individual data are depicted with gray lines in the panels' background. In (**b**), subplots display the women *vs*. men preference indices for each hue under the three noise conditions separately. The boundaries of the gray rectangles in the background of the subplots denote the minimum and maximum preference. Dark gray indicates the range of women's preferences, and light gray indicates the range of men's preferences.

are viewed under varying and non-uniform luminance conditions[14,15]. In this study, we introduced luminance noise to a mosaic stimulus as an initial step to approximate chromatic stimuli to real-world conditions without necessarily embedding them in a specific context (e.g., presenting color on a familiar object).

Initially, the inclusion of luminance noise significantly impacted the mean color preference indices. The condition with the highest luminance noise range (20 cd/m^2) resulted in significantly higher preference compared to both the no noise and intermediate noise conditions. Analyzing each hue individually confirmed the consistency of the luminance noise effect across all eight hues, with a notable preference difference between the no noise and highest range conditions, reflecting uniformity in participants' responses.

Previous studies have reported a preference for similar amounts of dark and light in natural scenes[27,28], concrete objects[29], and abstract stimuli[30]. This may explain our results, as the presence of noise to some extent approximates the chromatic stimuli used in the lab to those present in the real world. However, as discussed later, other factors beyond luminance need to be manipulated to create a more ecologically valid stimulus. The preference for noise presence can also be explained by efficient intensity processing in the visual cortex, as suggested by Graham et al.[28]. Images with similar proportions of light and dark areas seem to be more easily processed in early cortical levels, generating lower activation in V1[31]. As suggested in theoretical models of aesthetic processing, fluency processing can positively influence aesthetic judgments[32]. However, we observed differences between men and women in how luminance noise affects color preference, as discussed later. Consequently, this effect cannot be entirely attributed to the reported preference of V1 for luminance variation.

The inclusion of luminance noise resulted in an overall increase in preference, with no significant change in the shape of the preference curve, as indicated by the absence of a significant interaction between hue and luminance noise condition in mean preference. In other words, hues preferred under one noise condition remained preferred under others, demonstrating a more additive than transformative influence of luminance noise on color preference. Our color preference results align with the widely recognized "S"-shaped pattern, with blue being the most preferred color and yellow and chartreuse being the least[1], even with substantial individual variation[4]. In a paired-choice preference study examining eight isosaturation, isolightness colors[33], individual variations among 208 observers in hue-preference curves, amounting to a significant extent (70%), can be explained by the variance in the weights assigned to these two fundamental hue-encoding mechanisms. This effectively allows the identification of a shared collection of preference-encoding dimensions directly aligned with neural mechanisms. It enables the representation of individual differences in hue preference by the varying emphasis placed on the blue-yellow and red-green components.

A significant gender-related difference in color preference was found for the red, blue, purple, and chartreuse hues. Men demonstrated a higher preference for red, blue, and purple, while women favored chartreuse hues over men. Gender-related differences are frequently reported but inconsistently[2]. A meticulously conducted study revealed minimal variation in average preference patterns across different age groups. However, the study noted significant age-related differences between genders. Specifically, within the 18–22-year-old group, girls exhibited stronger preferences in the "purple" and "red–purple" range compared to boys, whereas boys leaned toward higher preferences in the "green" and "green-yellow" range[2]. Interestingly, our findings show exactly the opposite. Men preferred red and purple tones significantly more, while women preferred chartreuse hues. Ecological effects may be involved in gender-related differences in color preference[8], and further investigations are needed to explore the consistency of these differences in Brazilian populations and the ecological or non-ecological factors guiding these differences.

Although significant, the difference in color preference found in the highest luminance noise range condition in this study (20 cd/m^2) is relatively small considering the extent of the preference index (0–1.0). To verify the practical effects of luminance noise on color preference, we suggest testing different noise amplitudes above 20 cd/m^2. This will help determine whether the preference continues to increase, whether the effect is constant or non-linear, and whether it applies to all hues of interest.

Finally, we observed that the effect we found of luminance noise presence on color preference is predominantly driven by women's choices. Our results indicate that only women's color preference significantly increased in the presence of luminance noise, a pattern not observed in men. It is possible that men shape their aesthetic preferences by concentrating solely on the hue of the chromatic stimulus, while women take into account both the hue and the presence of luminance noise. These patterns can be explained in light of gender differences in spatial exploration strategies, as discussed by Cela-Conde et al.[34]: the activity of the parietal lobe, lateralized to the right hemisphere in men, may explain the greater emphasis on global features, while women, with bilateral activity, may integrate both global and local features in their aesthetic evaluations. Additionally, women tend to be more aware than men of different properties of stimuli, even when irrelevant to the task at hand, possibly as a consequence of gender-related differences in spatial attention[34–36]. We acknowledge that these explanations are highly speculative, and further investigation is needed to identify the factors contributing to these gender differences.

While our study introduced random luminance levels (luminance noise) to better approximate real-world conditions, we acknowledge that the artificial nature of the mosaic pattern and the presentation on a computer monitor rather than reflective surfaces still limit ecological validity. Further research should investigate color preference not only in the presence of luminance noise but also the manipulation of other chromatic characteristics, such as saturation, which were not varied in this study. An alternative approach could involve presenting stimuli with chromatic noise or a combination of chromatic and luminance noise.

Our results provide a comprehensive understanding of the impact of luminance noise on color preference, suggesting a positive influence, particularly for women. These findings support the idea that color preferences are linked to how we perceive colors in the real world, beyond the controlled laboratory environment, and contribute to our knowledge of gender differences in aesthetic color perception. This not only enhances the theory of color preference but also holds practical implications in fields such as design and visual communication.

Data availability
The data presented in this study are available in Supplementary Information.

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Author contributions
L.C.P.M. carried out the experiments, and contributed to conceptualization, methodology, data curation, formal analysis, data visualization, and writing—original draft preparation. F.A.C.B. was involved in software development for creating stimuli. E.M.C.B.L., P.R.K.G., L.M., M.F.C. and D.F.V. participated in the writing—review and editing. L.M. and M.F.C. also contributed to visualization and formal analysis. R.C.R. was involved in conceptualization, methodology, and supervision. G.S.S. was responsible for the supervision, formal analysis, methodology, conceptualization, data curation, formal analysis, writing—original draft preparation, writing—review and editing, and funding acquisition. All authors reviewed and approved the manuscript.

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Competing interests
The authors declare no competing interests.

Additional information
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