Seeing Your Screen Outside: Surround Effects on Brightness Discrimination

Denis Nikitenko
dnikiten@uoguelph.ca
University of Guelph
Guelph, ON, Canada

David R. Flatla
dflatla@uoguelph.ca
University of Guelph
Guelph, ON, Canada

Dixant Patel
dixant@uoguelph.ca
University of Guelph
Guelph, ON, Canada

Amanda Hahn
mandy@hahnmail.ca
University of Guelph
Guelph, ON, Canada

Uladzislau Kaparykha
vlad.kaparykha@gmail.com
University of Guelph
Guelph, ON, Canada

Kyle Lukaszek
klukasze@uoguelph.ca
University of Guelph
Guelph, ON, Canada

Nelith Ranaweera
nranawee@uoguelph.ca
University of Guelph
Guelph, ON, Canada

Graham Quinlan
graham.quinlan@proton.me
University of Guelph
Guelph, ON, Canada

Abstract

Situational visual impairments (SVIs) often make mobile screen content harder to distinguish in bright real-world settings. Re-analysis of an earlier large-scale dataset and our subsequent GI24 study together suggested that incident light on the display does not fully account for these effects, and that the luminance of the surrounding visual field is a likely contributor. In this paper, we investigate how surround luminance affects colour differentiation on a mobile display. We conducted a controlled study under three surround luminance conditions (35, 550, and 2000 cd/m^2) chosen using outdoor luminance measurements. Thirty-six participants completed just-noticeable-difference (JND) tests for 19 stimuli: 7 achromatic and 12 chromatic colours. Brighter surrounds produced larger JNDs across both achromatic and chromatic stimuli, with the effect concentrated at high L^* — JNDs at L^*=95 grew by approximately 60% from the dimmest to the brightest surround. A pooled cross-study comparison with our earlier work indicates that JNDs grew approximately three times faster per tenfold increase in illuminance when surround was directly manipulated than when only incident illumination on the screen was varied. Spectroradiometer measurements showed that reflected ambient light made only a small contribution to the luminance reaching the observer, supporting a perceptual rather than a purely physical interpretation. These findings argue for surround-aware extensions to mobile-display contrast guidelines, particularly for designs relying on subtle distinctions among light colours.

CCS Concepts

• **Human-centered computing → Empirical studies in accessibility**; *Accessibility systems and tools*; *Accessibility technologies*.

Keywords

HCI, accessibility, mobile computing, colour perception

ACM Reference Format:
Denis Nikitenko, David R. Flatla, Dixant Patel, Amanda Hahn, Uladzislau Kaparykha, Kyle Lukaszek, Nelith Ranaweera, and Graham Quinlan. 2026. Seeing Your Screen Outside: Surround Effects on Brightness Discrimination. In *Graphics Interface (GI26), June 9–12, 2026, Waterloo, ON, Canada.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3670947.3670959

1 Introduction

Human interaction with the digital world now takes place in a much wider range of environments than ever before. Mobile interactions often occur in busy, noisy settings with constantly changing conditions, far removed from the office or home environments that shaped earlier desktop computing. In these settings, the phone competes with the surrounding environment for visibility. Compared with an office monitor, mobile screens are much smaller, occupying a smaller portion of the user's field of view, and may be perceptibly darker than the surrounding environment. These conditions result in accessibility challenges for mobile interfaces, which have not yet been solved solely by engineering "better" displays, such as brighter screens or higher contrast.

The experience of being unable to see the contents of one's phone screen is likely familiar to everyone, and it is one example of a broader class of Situational Visual Impairments (SVIs) [24]. Prior work has shown that visibility and colour differentiation on mobile devices worsen under more challenging viewing conditions [9, 13, 17]. However, a re-analysis of an earlier large-scale dataset [17] revealed an unexpected pattern: while overall colour differentiability dropped sharply as viewing conditions became more challenging, this loss was driven primarily by reduced chromatic differentiation, with the achromatic (L^*) axis remaining comparatively stable [13]. Our subsequent GI24 study, which directly measured

ACM ISBN 979-8-4007-1828-1/24/06
https://doi.org/10.1145/3670947.3670959

achromatic differentiation under controlled bright conditions, was consistent with this pattern: direct illumination incident on the display had a relatively small effect on achromatic colour differentiation, whereas the lightness of the displayed content had a larger effect [13]. Together, these findings suggest that screen reflection and incident light alone do not fully explain bright-environment SVIs, and that additional contextual factors may be involved.

A likely missing factor is the luminance of the visual surround in which the display is observed. A mobile display is rarely seen in isolation. Instead, it is perceived relative to a much larger surrounding field that may be darker than, comparable to, or substantially brighter than the screen itself. In bright outdoor settings, the screen may therefore be perceived as a relatively dark stimulus within a bright surround—which is consistent with established surround effects on perceived brightness and contrast in the colour-appearance literature [1, 2]. This suggests that the relationship between screen luminance and surround luminance is an important factor affecting colour differentiability and overall display legibility.

In this paper, we investigate how colour differentiability on a mobile display changes as a function of surround luminance and displayed colour. We extend our earlier work by directly manipulating surround luminance relative to screen luminance and by expanding the stimulus set from seven achromatic colours used in an earlier study to 19 colours total, including 12 additional chromatic stimuli in the red, green, and blue regions of the sRGB gamut.

We make the following original contributions:

(1) We analyze how surround luminance affects colour differentiation on a modern mobile display. We conduct a study measuring just-noticeable differences (JNDs) under three surround luminance conditions spanning levels below, approximately equal to, and above the maximum display luminance. Using 19 test colours (7 achromatic and 12 chromatic), we show that brighter surrounds increase JNDs in a manner that depends on reference colour lightness, with the effect concentrated at high L*.
(2) We complement the perceptual study with spectroradiometer measurements of the displayed stimuli under each surround condition, allowing us to distinguish perceptual effects of the surround from simple reflected light.
(3) We compare the present results to those of our earlier achromatic study [13] through a pooled cross-study analysis, characterising how the relationship between surround conditions and achromatic JND differs when surround luminance is directly manipulated rather than incident illumination.

This work helps us better understand what factors contribute to SVIs on mobile devices, and how these factors might affect the appearance of mobile interfaces under challenging viewing conditions. Our results can help build the foundation for tools that can support designers in mitigating SVIs, such as practical interface design guidelines and SVI simulations.

2 Related Work

Visibility of a stimulus depends strongly on its luminance context: a given detail is harder to see against a brighter surrounding field than against a darker one.

2.1 Situational visual impairments during mobile interaction

On electronic displays, ambient light and visual surround affect contrast sensitivity, colour differentiation, and perceived image quality [8, 10, 11, 17]. These perceptual changes can have a negative effect on users' ability to complete tasks using digital interfaces. Prior work has shown that SVIs are experienced often during typical mobile tasks and can be frustrating for users [23]. Ambient light has also been shown to affect performance during everyday smartphone activities such as target acquisition and visual search, with less consistent effects on text entry [19]. Recent work on touchscreen use under situational visual impairment reported broader gestures, higher error in geometric-shape features, and timing effects that varied with users' familiarity with the gestures [9]. Collectively, this work shows that modern mobile interfaces remain susceptible to SVIs under both bright and reduced ambient light [9, 11, 19, 23].

While this work establishes SVIs as a real usability and accessibility problem, it says less about which perceptual properties of the display and its environment are driving the loss of visibility.

2.2 Display visibility under bright viewing conditions

The appearance of mobile interfaces in bright environments depends on many factors that interact in non-obvious ways. In such environments, the display can be darker than the surround, and the surround ratio (SR, surround luminance over display peak white) plays a role in the perception of screen content. The Bartleson–Breneman effect describes how perceived image contrast rises as surround luminance increases from dark toward typical room-illuminated conditions: dark areas of the image appear darker against brighter surrounds, expanding the apparent dynamic range of the image [2]. This effect informs the dark/dim/average surround compensation in colour appearance models (e.g., CIECAM02 [3]).

More recent work has shown that this relationship reverses once surround luminance exceeds display luminance: on a self-luminous display, the perceived brightness of light stimuli drops markedly as the SR rises above one. For example, Baek et al. measured perceived white brightness falling to approximately 70% of its dark-surround value at $SR \approx 6.7$ and to under 60% at $SR \approx 11.5$ [1].

As opposed to reflective media, emissive displays are limited by the luminance they can produce. As ambient and surround luminance increase, emissive displays can show degraded perceived brightness, contrast, and image quality [8, 11, 20].

This literature suggests that display visibility depends not only on incident illumination, but on the relationship between the display and the broader visual context in which it is viewed.

2.3 Colour appearance models and the need for ecologically valid data

HCI researchers and UI/UX designers are thus limited in their ability to predict or simulate the appearance of interface colours under specific viewing conditions. Reinecke et al. showed that users' colour differentiation abilities vary with environmental factors and proposed tooling to help designers anticipate colours that users may not reliably distinguish [17]. More broadly, HCI work on SVIs argues for better empirical data and better tools to support design for real mobile contexts [12, 23].

Colour-appearance models are relevant to our discussion because CIECAM02 and CIECAM16 are viewing-condition-specific frameworks that relate tristimulus values to perceptual appearance correlates [3, 4]. CIECAM02 was the CIE standard colour-appearance model for colour management systems (CIECAM16 is its official successor), with main applications including self-luminous displays [3, 4]. Within standard CIECAM02 practice, surround is reduced to three categories—dark, dim, and average—using SR thresholds of $SR = 0$, $SR < 0.2$, and $SR \geq 0.2$, respectively [7]. Consequently, conditions in which the surround is similar in luminance to the display and conditions in which the surround is substantially brighter than the display are not treated as distinct standard surround regimes, but are both absorbed into the broad average-surround class [7]. This matters for mobile use because bright-surround display studies found that standard CIECAM02 performed poorly under bright viewing conditions and introduced refined or corrected variants for mobile displays and veiling glare [15, 16].

All in all, the current body of research suggests studying the mobile screen not in isolation, but as a small self-luminous stimulus embedded within a much larger visual surround. This framing is particularly relevant for outdoor use, where the surround may be darker than, comparable to, or substantially brighter than the screen itself. However, there is little empirical data on how colour differentiability on a mobile display changes across controlled screen–surround luminance relationships, particularly when both achromatic and chromatic stimuli are considered.

Our study aims to complement existing research by providing empirical JND data on colour differentiability for a small emissive display viewed against controlled bright surrounds.

3 Surround luminance in common outdoor environments

To better define the surround conditions that we wanted to investigate in our experiment, we first measured the luminance of several common outdoor surfaces. These are the types of surfaces that can occupy much of a phone user's visual field during interaction. Although the measurements were not intended as an exhaustive survey of urban environments, they were used to establish whether realistic outdoor surrounds can be darker than, comparable to, or brighter than the maximum luminance of a mobile display. They were also used to provide empirical guidelines on the luminance of some of the typical surfaces in an urban setting.

The measured objects included concrete buildings, vegetation, and a wooden picnic table. Measurements were taken near the daily maximum solar elevation at University of Guelph's latitude (43°32′, Guelph, Ontario, Canada), approximately one hour after solar noon. All measurements were taken in areas that were not shaded by buildings or vegetation and were exposed to direct sunlight when the conditions were not cloudy. The illuminance during our measurements ranged from 33 000 lux (cloudy) to 104 000 lux (full sunlight). Maximum observed luminances were approximately 1500 cd/m^2 for green vegetation, 2200 cd/m^2 for a grey picnic table, 5000 cd/m^2 for light brown mulch, and 5600 cd/m^2 for a grey concrete building.

(a) Table with luminance of 2200 cd/m^2 in direct sunlight. **(b) Concrete with luminance of 5600 cd/m^2 in direct sunlight.**

Figure 1: Common outdoor surfaces that can occupy much of a mobile user's visual field during device use.

These measurements are not meant to be exhaustive—they are presented to illustrate the range of surround luminance values that a mobile device user might encounter in a sunny urban environment.

Contemporary smartphones can reach maximum white luminances on the order of 500–2000 cd/m^2, depending on the device and measurement conditions. Measurements we conducted prestudy (some shown in Figure 1) show that common outdoor backgrounds span a range of luminances that overlap with, and can exceed, the maximum white luminance of a mobile display. In practice, this means that a phone may be viewed under at least three distinct scenarios: one in which the screen is *brighter* than the surround, one in which the screen and surround are *similar* in luminance, and one in which the screen is *darker* than the surround.

We therefore designed our controlled study around three surround conditions intended to represent these scenarios. Specifically, we used one surround luminance below the device's maximum white luminance, one approximately matched to it, and one substantially above it. This allowed us to test how colour differentiability changes as the display shifts from being perceptually dominant to being embedded in a brighter surrounding field.

4 Colour differentiation tests

4.1 Study design and surround conditions

We conducted a colour-differentiation study to examine how JND varies with surround luminance and displayed colour. Surround luminance was manipulated between subjects to establish three viewing scenarios. Each participant was tested on 19 stimuli: 12 chromatic and 7 achromatic colours described below. The dependent variable was the just-noticeable distance (JND) measured using the C-test employed in earlier studies [13, 17].

The three viewing scenarios were as follows:

- 35 cd/m^2 - the surround was darker than the maximum screen luminance (*surround_35*).
- 550 cd/m^2 - the surround was comparable to the maximum screen luminance (*surround_550*).
- 2000 cd/m^2 - the surround was brighter than the maximum screen luminance (*surround_2000*).

Relative to the display's maximum white luminance of approximately 550 cd/m^2, these conditions correspond to surround ratios of approximately $SR = 0.064$, $SR = 1.0$, and $SR = 3.64$, using the standard CIECAM02 definition $SR = L_{SW}/L_{DW}$ [7]. Under the standard CIECAM02 surround thresholds, the first condition is dim, whereas the latter two are both classified as average surround [7]. We therefore treat the equal-luminance and brighter-surround cases as distinct empirical test conditions rather than assuming that they belong to the same perceptual regime, particularly in light of prior mobile-display work showing that bright surrounds challenge standard CIECAM02 and motivate refined treatments [15, 16].

In early pilot testing, we also explored a higher surround setting of approximately 3500 cd/m^2, which is close to the maximum luminance output of our apparatus. However, pilot participants reported that this surround was uncomfortable to view for extended periods, and some also noted discomfort from the radiant heat generated by the LED strips. We therefore set the highest surround condition in the present study to 2000 cd/m^2, which remained clearly brighter than the display's maximum white luminance while still being tolerable for the duration of the experiment. We leave higher surround luminance levels to future work.

We chose a between-subjects design to limit participant burden: a single condition takes 30–40 minutes (with a break after 20), so a within-subjects design would have required nearly two hours per participant and risked attrition that would compromise within-subject completeness. The trade-off is increased between-condition variance from individual differences, which we mitigated through random assignment, equal cell sizes (12 participants per condition), and a participant random effect in the analysis.

4.2 Participants

In total, 41 participants were recruited for our study. We excluded five participants during preliminary data screening as their data was incomplete or failed our quality-control criteria. We used the data from the remaining 36 participants, with 12 participants for each surround luminance level. In total, 24 participants were male (mean age: 23.6 years) and 12 were female (mean age: 23.4 years).

All participants had either normal or corrected-to-normal visual acuity, and all were screened to ensure that no one had colour vision deficiency using an online Ishihara Plate Test [5].

4.3 Experimental apparatus

The experimental apparatus consisted of a mobile device housed within a custom-built light box used to create different surround luminances under simulated indoor and outdoor illumination conditions. A mobile phone-sized portion of the device screen was visible through a rectangular aperture centered on the back of the box (see Figure 2). This setup was intended to simulate a phone viewed against a surround of controlled luminance while isolating the display from ambient conditions in the lab.

A set of four D65 LED light strips (99 CRI) was used to illuminate the apparatus. These lights were mounted around the outer perimeter of the box to provide even diffusion of light across the device surround. They were facing the surround with the mobile device behind it and hidden from the viewer (Figure 2), and neither the light sources themselves nor their individual reflections were visible to participants. The light strips were controlled with an external dial that allowed the experimenters to set the light incident on the mobile device, and therefore the surround luminance level.

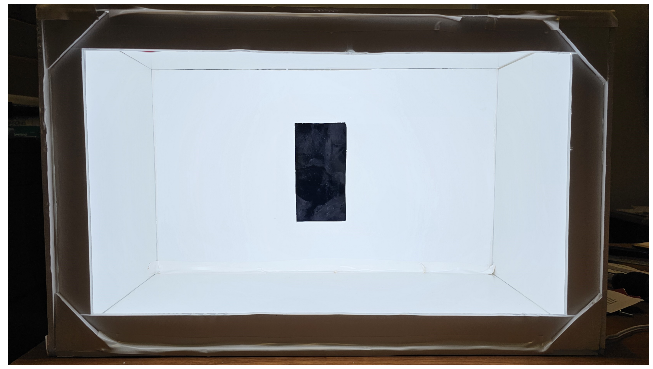

Figure 2: Participant view of experimental apparatus.

The illumination produced by the light strips was measured using a light meter centered in the mobile device aperture facing the lights. The surround luminance was measured with a spectroradiometer at eight evenly distributed points around the aperture. The luminance values varied by approximately 5% between the measurement points and were averaged for each condition during analysis.

The mobile device used for this study was an 11-inch iPad Pro tablet, 4th generation (model A2759). Screen brightness was fixed at 100% for all conditions to simulate a realistic outdoor-use scenario, as many modern mobile devices automatically increase brightness in response to strong environmental light. Additional display modes such as "true-tone" and "night-shift" were disabled because they would introduce confounding factors by altering the appearance of the screen contents. This device was selected because we used it in our earlier study [13], facilitating comparison with prior results. In addition, its maximum brightness of 550 cd/m^2 is lower than that of current flagship mobile devices. We therefore considered it more representative of the broader range of mobile displays currently in use, including older phones, budget phones, and touchscreen devices such as vehicle infotainment systems.

4.3.1 The C-test. The C-test, originally introduced by Flatla and Gutwin [6], measures the smallest perceivable difference between a base colour and a search colour along a fixed line in CIE L*u*v* colour space. On each presentation, the participant is shown a 400×400 px stimulus consisting of a stylised "C" shape against a background (see Figure 3), where both the C and the background are filled with dynamic spatial-and-temporal luminance noise (per-pixel, per-frame L* offsets drawn uniformly from $\{-5, -4, \ldots, 4, 5\}$ in CIE L*u*v* units) to suppress chromatic-contrast cues and reduce adaptation effects. The participant identifies the orientation of the gap in the C among eight possible directions (red arrows in Figure 3), or indicates that the gap cannot be resolved. A correct identification is treated as a differentiable response; an incorrect identification or "can't tell" response is treated as not differentiable.

For each test colour, the search is conducted along a pre-computed sequence of sRGB colours of increasing distance from the base. The procedure is an adaptive *binary search* over this sequence: the first presentation tests the most distant colour from the base, and each subsequent presentation tests the midpoint of the current bracket, with the bracket narrowed on each response (the upper bound is

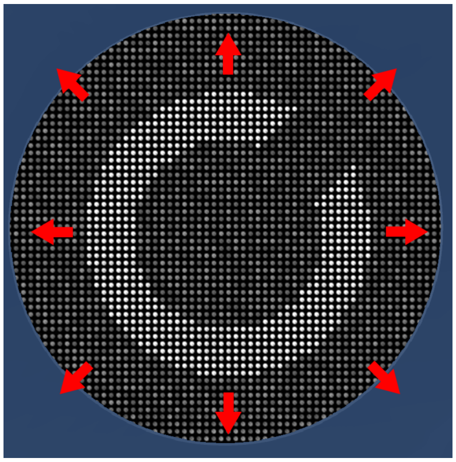

Figure 3: Example C-test stimulus. The participant identified the gap direction using the corresponding numeric keypad key; a correct response indicated that the foreground and background colours were differentiable for that trial.

tightened on a differentiable response; the lower bound is tightened on a non-differentiable response). The trial ends when the bracket narrows to two adjacent indices, at which point the JND for that colour and search direction is recorded as the L*u*v* distance between the base and the converged bracket midpoint. As binary search converges in $\sim \log_2(N)$ presentations for a line of N colours, participants saw 6–10 presentations per trial in this study.

Each participant completed 19 stimuli $\times$ 2 search-direction combinations (giving 33 trials in total, as five boundary stimuli had only one feasible search direction within the sRGB gamut) at three repetitions each, for 99 testing trials per participant. Trials were preceded by 30 training trials drawn from the same colour set, presented at the maximum search distance to familiarize participants with the gap-identification task. Testing trials were interleaved in a round-robin schedule across stimuli and repetitions: each round presented one bisection step from every active trial, after which the remaining trials were reshuffled, ensuring that consecutive presentations rarely came from the same colour. A break was offered automatically after the first 20 minutes of testing, with a brief warm-up block on resumption.

4.4 Stimuli and colour selection

This study was designed to explore the impact of surround brightness on both chromatic and achromatic colours.

4.4.1 Achromatic colours. Seven achromatic test colours were sampled evenly along the L* axis of the CIE L*u*v* colour space. Each test colour was presented multiple times, both with a "C" colour that was lighter (except for L*=95) and darker (except for L*=5) than the background. These colours allow for direct comparison with results obtained earlier (GI24 [13]). Continued use of achromatic stimuli is consistent with our motivating focus on the L* axis, where the re-analysis of the Reinecke et al. data first identified the unexpected stability of achromatic differentiability under increasingly challenging viewing conditions [13, 17].

4.4.2 Chromatic colours. Chromatic colours were selected to maximize chroma range while remaining within the device gamut and compatible with the C-test search procedure. First, each sRGB primary colour with the maximum chroma (i.e. (255,0,0), (0,255,0), and (0,0,255)) was converted to the CIE L*u*v* colour space. These three colours are the points of the sRGB gamut in CIE L*u*v* space that lie the farthest from the L* axis, and thus have the highest chroma value. An isoluminant line was then computed from each of these three points to the L* axis (visible in Figure 4). The following colours were then selected along each isoluminant line:

- Colours 1/3 and 2/3 of the distance between the L* axis and the corresponding corner of the sRGB gamut. These are the colours with subscripts $_{1/3}$ and $_{2/3}$ in Figure 4 and Table 1.
- For R and B: colours 15 units above and below the 1/3 location on each isoluminant line: subscripts $_{1/3-15}$ and $_{1/3+15}$ in Figure 4 and Table 1.
- For G: colours 15 units and 30 units below the 1/3 location: $G_{1/3-15}$ and $G_{1/3-30}$ in Figure 4 and Table 1.

The green colour 15 units above the 1/3 point along the green isoluminant line was not selected because it fell outside the sRGB gamut. A second colour 30 units below the 1/3 point on the G isoluminant line was selected instead ($G_{1/3-30}$ in Figure 4).

Note that, as can be seen from Figure 4, the 19 resulting colours are generally not isoluminant—the blue colours with high chroma, for example, are significantly darker than the green colours with a high chroma, due to the different sensitivities of the corresponding cones in the human eye.

Figure 4 illustrates the sampled colours in CIE L*u*v* space (also listed in Table 1). The sRGB gamut is visible as a "misshapen diamond", and the three maximum values of sRGB primaries correspond to the red, green, and blue corners of the sRGB gamut. The 19 sampled colours are indicated using white circles, the vertical lines show the search spaces explored by the C-test around each colour, and the horizontal lines help illustrate the sampling.

4.5 Procedure

We conducted the study in a lab with controlled ambient illumination. Room lighting was approximately 400 lux, and the apparatus was the only light source within the participant's field of view. The apparatus was placed on an adjustable desk, with a covered window behind the participant. Both the mobile device and the lights in the apparatus were turned on at least 15 minutes prior to the start of each trial. The iPad was set to maximum brightness and the LED light strips were adjusted to the desired setting, to give both of them sufficient time to reach luminance stability.

The desk height was adjusted for each participant so that the participant's line-of-sight was aimed directly into the apparatus and was orthogonal to the iPad Pro surface when they were sitting comfortably. The viewing distance was set to approximately 50 cm. The apparatus took up the majority of the participant's field of view. Each participant was given a 5-minute (30 trials) training session to familiarize them with the apparatus and let their visual system adapt to the lighting environment presented to them. After the training was complete, the participant conducted a single C-test session, with a break after approximately 20 minutes.

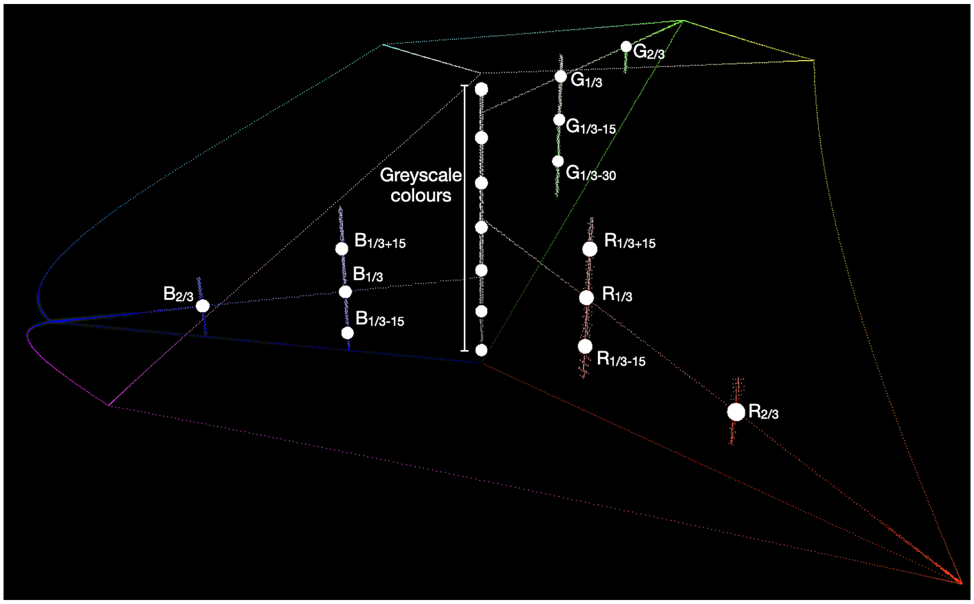

Figure 4: Sampled colours in CIE L*u*v* colour space.

Table 1: A list of colours selected as test colours for all conducted studies: test colours in CIE L*u*v* space, their approximate sRGB conversion (D65 illuminant), colour patches, and text labels used to refer to them in this work.

Greyscale test colours				Red test colours				Green test colours				Blue test colours			
CIE L*u*v*	RGB	Patch	Label	CIE L*u*v*	RGB	Patch	Label	CIE L*u*v*	RGB	Patch	Label	CIE L*u*v*	RGB	Patch	Label
(5, 0, 0)	(17, 17, 17)		L5	(53, 57, 12)	(186, 104, 104)		$R_{1/3}$	(88, -27, 35)	(179, 234, 179)		$G_{1/3}$	(32, -3, -43)	(70, 70, 125)		$B_{1/3}$
(20, 0, 0)	(48, 48, 48)		L20	(68, 57, 12)	(228, 143, 143)		$R_{1/3+15}$	(73, -27, 35)	(137, 192, 137)		$G_{1/3-15}$	(47, -3, -43)	(107, 107, 160)		$B_{1/3+15}$
(35, 0, 0)	(82, 82, 82)		L35	(38, 57, 12)	(146, 65, 65)		$R_{1/3-15}$	(58, -27, 35)	(96, 152, 96)		$G_{1/3-30}$	(17, -3, -43)	(33, 33, 102)		$B_{1/3-15}$
(50, 0, 0)	(119, 119, 119)		L50	(53, 115, 25)	(225, 73, 73)		$R_{2/3}$	(89, -55, 71)	(128, 245, 128)		$G_{2/3}$	(32, -6, -87)	(59, 59, 178)		$B_{2/3}$
(65, 0, 0)	(158, 158, 158)		L65												
(80, 0, 0)	(198, 198, 198)		L80												
(95, 0, 0)	(241, 241, 241)		L95												

5 Results

5.1 Analysis overview

We collected JND measurements for 19 colours under three viewing environments, with 12 participants per environment. Each participant completed the colour-differentiation task for all 19 colours, with three measurements per participant–colour combination averaged for analysis. Initial data-quality checks showed that all 36 participants were uniquely assigned to a single environment condition, with no missing values in the key analysis variables.

All Section 5 analyses use linear mixed-effects models with a participant random intercept; the model family for each subsection is summarised in Table 2. Final models in each subsection were selected from nested specifications via likelihood-ratio tests at $\alpha = 0.05$, refit with REML, and used as the basis for the reported coefficients, contrasts, and confidence intervals.

Overall, observed JNDs tend to increase with the luminance (L*) of the reference colour, and higher-surround conditions tend to be associated with larger JNDs. This can be seen in Figure 5, which groups colours by hue. Within each hue, colours in Figure 5 are arranged as much as possible by luminance, although the "1/3" and "2/3" colour pairs of the same hue are isoluminant.

Across all 19 colours, the mixed-effects model showed significant main effects of surround condition, $F(2, 31) = 8.38$, $p = .0012$, and colour, $F(18, 594) = 36.31$, $p < .001$. Holm-adjusted pairwise comparisons showed that mean JND was significantly lower in *surround_35* than in *surround_550* and *surround_2000*, while the difference between *surround_550* and *surround_2000* was not statistically significant. Age was also a significant covariate, $F(1, 31) = 8.03$, $p = .0080$, whereas sex was not, $F(1, 31) = 0.08$, $p = .774$, and was the surround × colour interaction, $F(36, 594) = 1.38$, $p = .071$.

5.2 Greyscale results

Across the seven greyscale stimuli, JND varied significantly with greyscale L*, $\chi^2(2) = 143.98$, $p < .001$, indicating that participants

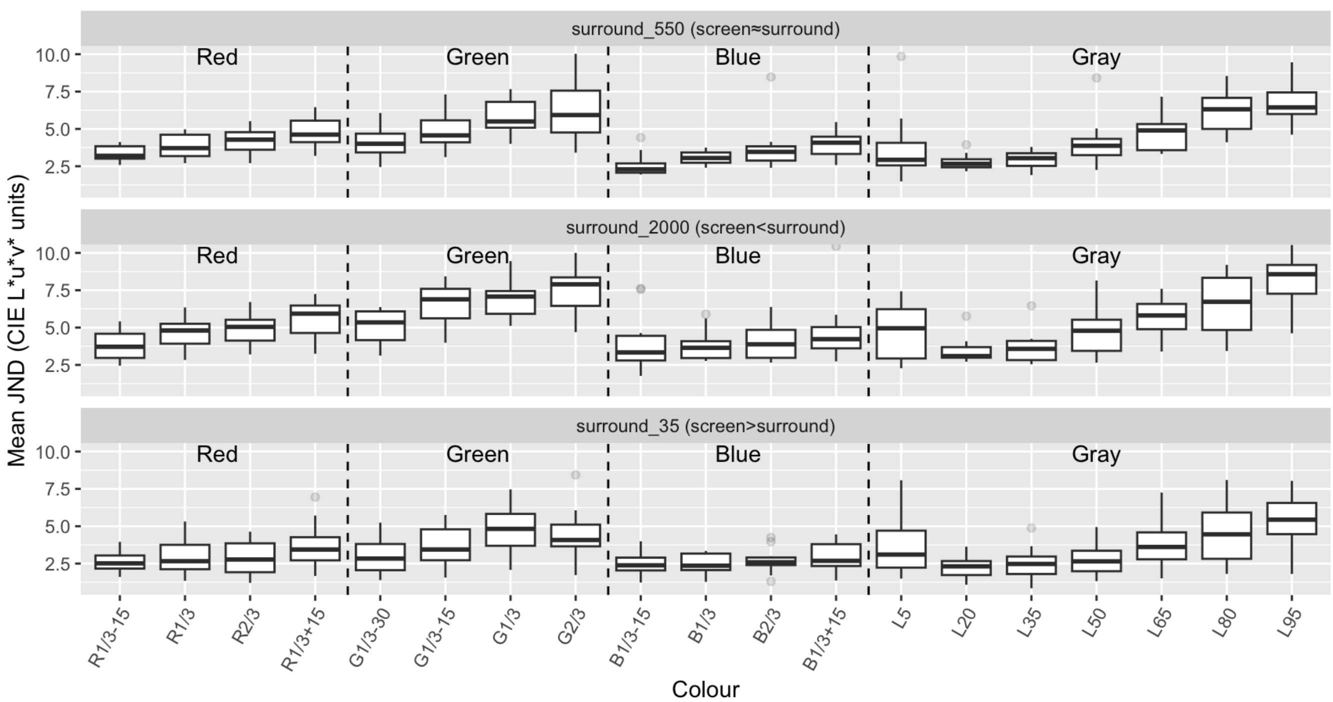

Figure 5: JND distribution across all 19 colours and 3 environments.

Table 2: Summary of the statistical model families used in Section 5. Each row corresponds to one analysis subsection. All models are linear mixed-effects models; nested specifications were compared with likelihood-ratio tests at $\alpha = 0.05$, and the final selected model was refit with REML. The participant random intercept is denoted $(1 \mid uuid)$; for the cross-study analysis, $(1 \mid study\_uuid)$ pools participants across studies. Bracketed terms in each model family indicate the optional/extra terms compared in the model-selection cascade.

Question	Model family	Final model
Are surround and colour main effects present? Does surround interact with colour? (§5.1)	distance ∼ env × colour_label + age + sex + $(1 \mid uuid)$	Interaction model (type-III ANOVA)
Does JND vary with greyscale L*? Does surround shift the curve, change its shape, or both? (§5.2)	distance ∼ env [$*\,\mathrm{poly}(L^*, 2)$] + age + sex + $(1 \mid uuid)$	Additive (no env × L* shape change)
Does JND vary with L* differently across RGB primaries? Does surround change the slope? (§5.3)	distance ∼ env [+ env:L*]+primary×L*+age+sex+$(1 \mid uuid)$	Slope-interaction (env × L*)
Do paired chromatic stimuli differ in JND, and does the difference depend on surround? (§5.3)	distance ∼ env [∗ variant] + primary + age + sex + $(1 \mid uuid)$	Interaction model (env × variant)
Does the L*–JND relationship across the full set differ by surround? (§5.4)	distance ∼ env [$*\,\mathrm{poly}(L^*, 2)$] + age + sex + $(1 \mid uuid)$	Interaction model (env × L* shape change)
Is the age effect linear, quadratic, or surround-dependent? (§5.5)	distance ∼ env × colour_label + age [+ age^2] [+ env:age] + sex + $(1 \mid uuid)$	Additive linear-age model
Does the L*–JND shape or context effect differ between GI24 and GI26? (§5.6)	distance ∼ dataset [$*\,\mathrm{poly}(L^*, 2)$] [∗ context] + $(1 \mid study\_uuid)$	Dataset × L* interaction (no dataset × context)
Does the JND-vs-illuminance slope differ between GI24 and GI26? (§5.6)	$\log_{10}$(distance) ∼ dataset [$*\,\log_{10}(\mathrm{lux})$] + dataset × $\mathrm{poly}(L^*, 2)$ + $(1 \mid study\_uuid)$	Slope-interaction on loglog scale (p = .007)

had greater difficulty differentiating brighter greyscale colours. There was also a significant overall effect of surround condition after accounting for greyscale L*, $\chi^2(2) = 12.16$, $p = .0023$. However, allowing the greyscale curve to vary by surround condition did not significantly improve model fit, $\chi^2(4) = 7.76$, $p = .1009$, indicating that surround primarily shifted the greyscale JND curve rather than changing its shape. Predicted mean JNDs were lowest

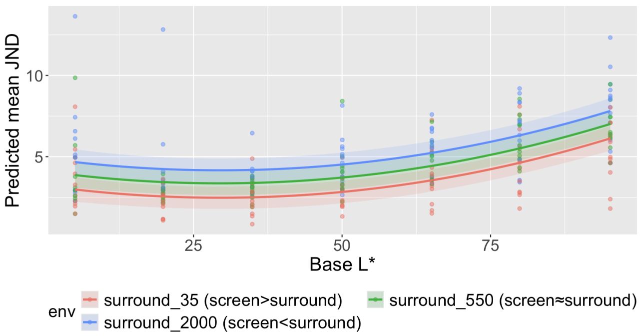

Figure 6: Summary of the greyscale data using an additive mixed-effects model with a quadratic L* trend and an overall surround effect. Shaded ribbons show 95% CIs.

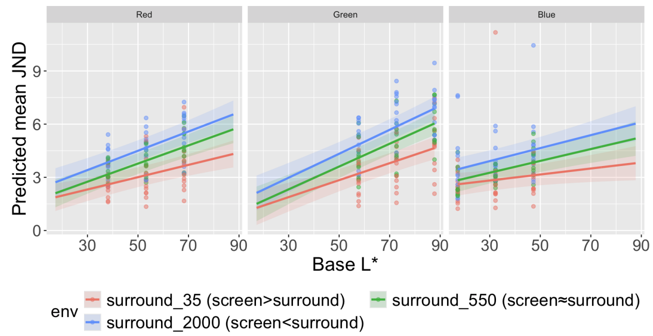

Figure 7: Chromatic 1/3-family JNDs from the mixed-effects model with primary-specific L* trends and a surround × L* interaction. Shaded ribbons show 95% confidence intervals.

in *surround_35* and increased as the surround became brighter. The effect of the environment and L* on the JND can be seen in Figure 6.

Holm-adjusted pairwise comparisons at representative greyscale values (L* = 5, 50, and 95) showed that predicted mean JND was lower in *surround_35* than in *surround_2000*. This difference was statistically significant at L*=50 (difference = −1.39, 95% CI [−2.72, −0.06], $p = .038$) and at L*=95 (difference = −2.56, 95% CI [−4.14, −0.98], $p < .001$), but not at L*=5 after Holm adjustment ($p = .054$). Differences between *surround_35* and *surround_550*, and between *surround_550* and *surround_2000*, were not statistically significant at the representative lightness values after adjustment. Overall, these results indicate reduced greyscale differentiability in brighter surrounds, although the effect of greyscale L* remained larger than the effect of surround.

5.3 Chromatic results

Unlike the greyscale colours, which lie on a single achromatic line in CIE L*u*v* space, the red, green, and blue colours used in this study occupy different regions of the sRGB gamut, as seen in Figure 4. For each hue, three of the colours share the same chromatic coordinates: the "1/3" colour and the colours above and below it. Each hue also includes a pair of isoluminant colours: the "1/3" and "2/3" colours. We therefore analyzed the chromatic data in two steps:

- We fit a linear model to the three sets (R, G, and B) of three colours sharing the same u* and v* coordinates. These three colour sets (the "1/3-family") are: $\{R_{1/3}, R_{1/3-15}, R_{1/3+15}\}$, $\{G_{1/3}, G_{1/3-15}, G_{1/3-30}\}$, and $\{B_{1/3}, B_{1/3-15}, B_{1/3+15}\}$ located on the three chromatic vertical lines in Figure 4.
- We then conducted pairwise comparisons of the isoluminant colours of each hue: $\{R_{1/3}, R_{2/3}\}$, $\{G_{1/3}, G_{2/3}\}$, and $\{B_{1/3}, B_{2/3}\}$.

For the nine chromatic 1/3-family colours, the model-comparison analysis showed that JND varied significantly with reference L*, with the relationship between JND and L* differing across the three primaries, $\chi^2(3) = 110.64$, $p < .001$. After accounting for these chromatic L* trends, there was also a significant overall effect of surround condition, $\chi^2(2) = 14.74$, $p = .00063$. Unlike the greyscale analysis, however, allowing surround to modify the chromatic L* slope significantly improved model fit, $\chi^2(2) = 13.09$, $p = .0014$. The effect of the environment on the JND for the colours in this set can be seen in Figure 7.

Holm-adjusted pairwise comparisons averaged over the three primaries showed that mean JND was significantly lower in *surround_35* than in *surround_2000* ($\Delta = -1.54$, $p = .0012$), whereas the differences between *surround_35* and *surround_550* ($\Delta = -0.81$, $p = .0863$) and between *surround_550* and *surround_2000* ($\Delta = -0.73$, $p = .0863$) did not reach significance after adjustment. As before, chromatic differentiability depended on reference L* and brighter surrounds increased chromatic JND.

Our analysis of the "1/3" and "2/3" chromatic colour pairs showed that the JNDs for each colour pair did not differ overall. A model adding variant (13 vs. 23) did not fit better than a model without it, $\chi^2(1) = 1.91$, $p = .167$. However, the "1/3" vs. "2/3" difference varied with surround: adding the variant × surround interaction improved fit, $\chi^2(2) = 6.66$, $p = .036$.

5.4 Overall relationship between JND, surround luminance, and L*

To investigate whether the greyscale pattern observed in Section 5.2 reflected a broader relationship between L*, JND, and the surround luminance in the full dataset, we fit an analogous mixed-effects model to all 19 colours after projecting them onto the L* axis. In this analysis, each stimulus retained its reference L* value, while chromatic differences in u* and v* were not modelled directly.

JND varied significantly with projected L*, $\chi^2(2) = 425.84$, $p < .001$, indicating a strong nonlinear relationship between projected lightness and colour differentiability. There was also a significant overall effect of surround condition after accounting for projected L*, $\chi^2(2) = 15.56$, $p < .001$. Unlike the greyscale-only analysis, however, allowing the projected-L* curve to vary by surround condition significantly improved model fit, $\chi^2(4) = 28.33$, $p < .001$, indicating that surround condition altered both the overall level of JND and the shape of its relationship with projected L*. The effect of the environment on the JND for the colours projected onto the L* axis can be seen in Figure 8.

Model-based pairwise comparisons at representative projected lightness values (L* = 5, 50, and 95) showed that the brightest surround generally produced the highest predicted JNDs. At L*=5, both

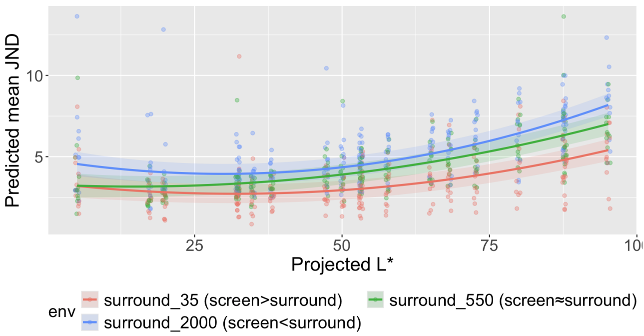

Figure 8: Summary of the projected-L* analysis for all 19 colours using a mixed-effects model with a quadratic projected-L* term, surround condition, and their interaction. Shaded ribbons show 95% confidence intervals.

surround_35 and *surround_550* yielded significantly lower predicted JNDs than *surround_2000* (difference = −1.35, 95% CI [−2.63, −0.08], p = .033; and difference = −1.34, 95% CI [−2.60, −0.08], p = .033, respectively), while *surround_35* and *surround_550* did not differ significantly (p = .973). At L*=50, predicted JND remained significantly lower in *surround_35* than in *surround_2000* (difference = −1.41, 95% CI [−2.46, −0.36], p = .005), while the differences between *surround_35* and *surround_550* (p = .051) and between *surround_550* and *surround_2000* (p = .284) were not significant after Holm adjustment. At L*=95, all three surround conditions were more clearly separated: predicted JND was lower in *surround_35* than in both *surround_550* (difference = −1.60, 95% CI [−2.79, −0.42], p = .0029) and *surround_2000* (difference = −2.77, 95% CI [−3.97, −1.58], p < .001), and lower in *surround_550* than in *surround_2000* (difference = −1.17, 95% CI [−2.35, 0.01], p = .017). Overall, these results suggest that the effect of surround luminance on differentiability becomes more pronounced toward the higher end of the projected-L* range.

Taken together with Sections 5.2 and 5.3, this analysis suggests that the greyscale result reflects a broader luminance-dependent pattern rather than an effect limited to the achromatic stimuli alone. At the same time, because this projection collapses chromatic differences, it should be interpreted as a supplementary analysis rather than a substitute for the chromatic models in Section 5.3.

5.5 Effects of age on JND

We observed a significant effect of age on the JND in the initial analysis, which we investigated in more detail. To test whether JND varied with participant age, we extended the mixed-effects model from Section 5.1 by adding age terms while retaining surround, colour, sex, and a participant random intercept. Adding a linear age term significantly improved model fit relative to the no-age model ($\chi^2(1) = 8.29, p = .004$), indicating an overall association between age and JND. However, adding a quadratic age term did not further improve fit ($\chi^2(1) = 0.94, p = .331$), providing no evidence for a nonlinear age effect. Allowing the age slope to vary by surround also did not significantly improve fit at the $\alpha = .05$ level ($\chi^2(2) = 5.53, p = .063$).

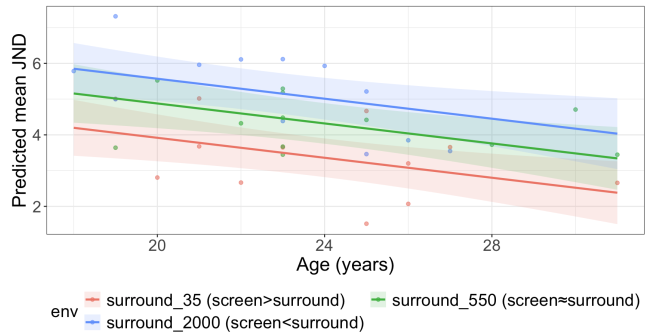

Figure 9: Model-adjusted JND by participant age and surround, averaged across the 19 tested colours. Lines show model predictions, shaded bands show 95% confidence intervals, and points show participant-level mean JNDs.

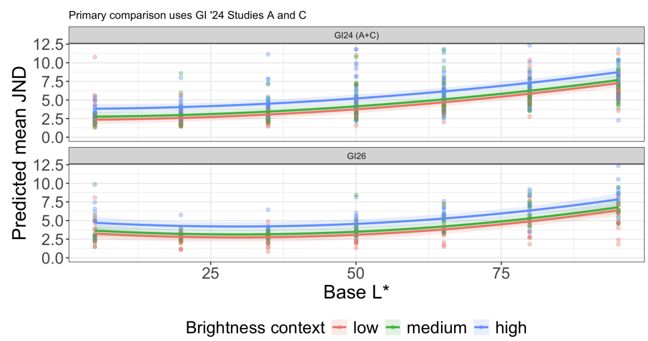

Figure 10: Fitted greyscale JNDs for GI24 and GI26 by reference lightness (L*) and context. Lines show predictions from the pooled mixed-effects model, and shaded regions show 95% confidence intervals.

In the final model, age remained a significant predictor ($F(1, 31) = 8.03, p = .008$), with an estimated slope of −0.140 JND units per year (95% CI [−0.240, −0.039]). Expressed over a decade, this corresponds to an estimated change of approximately −1.40 JND units (95% CI [−2.40, −0.39]), as can be seen in Figure 9.

5.6 Cross-study comparison of greyscale JNDs

We conducted a cross-study comparison using the current data together with data from studies A and C in our GI24 work, as these environments were the most directly comparable to the present study [13]. In the pooled analysis, JND varied significantly with greyscale lightness and context. Adding the quadratic lightness term substantially improved model fit relative to a model without lightness, $\chi^2(2) = 283.41$, $p < 2.2 \times 10^{-16}$, and adding context also improved fit, $\chi^2(2) = 44.76$, $p = 1.91 \times 10^{-10}$. The categorical context effect (low / medium / high) was comparable across the two datasets: allowing it to differ by dataset did not improve model fit, $\chi^2(2) = 1.09$, $p = .579$. Despite the different experimental manipulations used to create it (surround luminance in GI26, incident illumination on the screen in GI24), context had a similar overall effect on JND in both datasets (Figure 10).

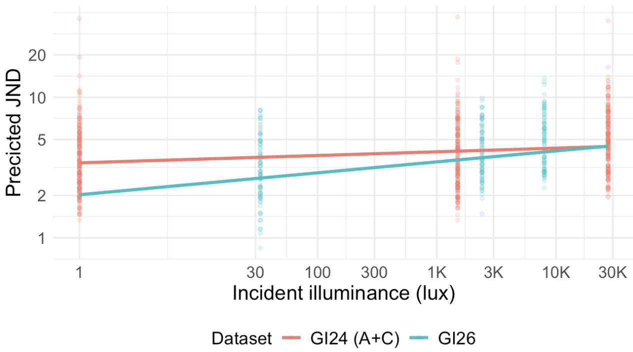

Figure 11: Predicted L* JND (in CIE L*u*v* units) as a function of incident illuminance (lux). Slopes: GI24 = 0.026, GI26 = 0.078 (log10 JND per log10 lux).

The relationship between JND and greyscale lightness differed significantly between datasets, $\chi^2(2) = 12.28$, $p = .002$. As shown in Figure 10, GI26 produced a flatter L*-JND curve than GI24, with relatively higher JNDs at low L* and relatively lower JNDs at high L*. A complementary log-scale comparison estimated the GI24/GI26 JND ratio to be 0.78 (95% CI [0.66, 0.91], $p = .002$) at L*=5 and 1.16 (95% CI [1.01, 1.33], $p = .036$) at L*=50, with no significant difference at L*=95 ($p = .44$). Thus, the cross-study difference was not a uniform upward shift in JND, but a change in the shape of the lightness-dependent trend.

We also conducted a pooled analysis to test whether the relationship between JND and incident illuminance differed across studies. A log-distance scale is a natural choice for relating JND to physical intensity under classical psychophysical models (Weber's Law and Stevens' power law), and we use it as our primary analysis here. In this analysis, the per-study slopes were 0.026 for GI24 (95% CI [0.020, 0.032]) and 0.078 for GI26 (95% CI [0.041, 0.115]), with non-overlapping confidence intervals (interaction $p = .008$). A raw-scale slope-difference test was borderline ($p = .055$), reflecting leverage from the most extreme GI24 illuminance level (27 500 lux, well outside the GI26 range).

As seen in Figure 11, at equivalent illuminance, the GI26 surround manipulation produced JND growth approximately three times faster per tenfold increase in illuminance than GI24's incident-only manipulation. This indicates that surround luminance is a separable contributor to colour differentiation in the mobile context, distinct from incident illumination on the screen alone. Given the limited overlap in illuminance ranges across studies and the differing physical layouts of the two viewing boxes (a surround vs. direct illumination of the screen), this slope difference should be interpreted as suggestive rather than definitive evidence of a surround-specific contribution.

6 Spectroradiometer measurements

The above results do not indicate whether the observed JND changes arose primarily from the visual surround as perceptual context or from physical changes in the light leaving the display and reaching the observer. To assess the possible contribution of reflected ambient light, we complemented the perceptual study with spectroradiometer measurements of the stimuli under the same illumination conditions. We used a JETI spectraval 1501 spectroradiometer to measure the 19 sample colours displayed on the iPad under the three light settings used to create the surround conditions in this study. For each colour, we recorded luminance (in cd/m^2), shown in Table 3. These measurements indicate that reflected light made a very small contribution to the luminance of the achromatic stimuli, with the largest changes observed for the darkest greys.

Table 3: Recorded luminance (cd/m^2) for the 19 tested colours under the low, medium, and high surround conditions. Colours are identified by reference CIE $L^*u^*v^*$ coordinates, rounded to the nearest integer.

Ref. $L^*u^*v^*$	*surround_35*	*surround_550*	*surround_2000*
(5, 0, 0)	2	4	11
(20, 0, 0)	15	17	24
(35, 0, 0)	47	50	56
(50, 0, 0)	108	110	117
(65, 0, 0)	203	205	213
(80, 0, 0)	339	340	351
(95, 0, 0)	525	525	539
(53, 59, 13)	124	126	134
(68, 59, 13)	227	228	237
(38, 58, 11)	57	60	66
(53, 116, 25)	124	126	133
(88, −28, 36)	429	429	440
(73, −28, 36)	267	268	277
(58, −28, 36)	151	153	160
(88, −55, 71)	425	426	437
(32, −3, −43)	40	42	49
(47, −3, −44)	95	96	103
(17, −3, −44)	12	14	21
(32, −6, −87)	41	43	50

7 Discussion

This study shows that surround luminance contributes to reduced colour differentiation—including reduced lightness differentiation—on mobile displays. Brighter surrounds generally produced larger JNDs, an effect that was observed across all tested environments and colours and was systematic across the L* range. For example, the maximum JND at L*=95 increases from approximately 5 units when the surround is darker than the screen ($SR = 0.064$) to approximately 8 units when the surround is brighter than the screen ($SR = 3.64$)—a 60% increase. Cross-study analysis showed that the JND-vs-illuminance relationship was approximately three times steeper in the present study than in our earlier work without surround manipulation, indicating that surround luminance is a separable contributor to bright-environment SVIs distinct from incident light on the screen alone.

Spectroradiometer measurements indicate that reflected ambient light made a small contribution to the luminance reaching the observer. This contribution does not appear sufficient on its own to account for the observed increase in JNDs, which strengthens the interpretation that surround luminance influenced colour differentiation through perceptual factors rather than physical changes in stimulus luminance.

The observed pattern is consistent with established findings on surround effects in colour appearance. As surround luminance rises above display luminance, perceived brightness of light stimuli on a self-luminous display drops markedly [1], an extension of the classical Bartleson–Breneman effect [2] for $SR > 1$, which is common outdoors, where mobile use typically occurs. Although this perceptual mechanism does not explain every aspect of our results—in particular, the L*-dependent shape of JNDs was already present in our earlier work without surround manipulation [13], indicating multiple contributors—the perceptual machinery linking surround luminance to reduced colour differentiability is well-established. Our results show that this machinery contributes to bright-environment SVIs on small mobile displays.

JNDs were larger for lighter colours across both achromatic and chromatic stimuli. Our supplementary projection of all 19 colours onto the L* axis was consistent with this pattern, indicating that the effect is not limited to achromatic stimuli. The relationship is consistent with luminance-pedestal findings showing threshold elevation at higher achromatic pedestal levels [22], although we worked in CIE L*u*v* rather than the cone-contrast space typical in vision research, so the comparison is qualitative.

These results have direct implications for mobile interface design. The effect concentrates at high L*: differences between near-white colours in the brightest viewing conditions become substantially harder to discriminate, while distinctions among darker colours remain comparatively stable. In practice, this means that interfaces using subtle distinctions between light shades—light-grey-on-white text, low-contrast buttons against pale backgrounds, light pastel palettes—are most vulnerable to bright-environment SVIs, whereas designs using darker accents, high-luminance-contrast layouts, or redundant non-colour cues (e.g. text labels or outlines) preserve more differentiability outdoors. This affects everyone using a mobile device in bright conditions, not only people with permanent visual impairments. Current mobile-display contrast guidelines, including the WCAG 2.0 4.5:1 ratio for normal text [25], derive from controlled viewing conditions and treat contrast as a single scalar independent of surround. Our findings show that perceptual differentiability is surround-dependent in the conditions where mobile devices are commonly used, suggesting that surround-aware extensions to existing contrast guidelines—rather than a single ratio applied universally—may better match those conditions. Tools such as ColorCheck [17], which let designers see which colour pairs become indistinguishable to a population, can provide surround-aware support for UX designers.

Because most of the colours in our study were not isoluminant, we could not fully separate the effects of hue, chroma, and surround luminance. However, for colour pairs that shared hue and lightness and differed only in chroma—$(R_{1/3}, R_{2/3})$, $(G_{1/3}, G_{2/3})$, and $(B_{1/3}, B_{2/3})$—there was no significant overall difference in JND when these pairs were averaged across surrounds, although the 1/3-versus-2/3 difference varied by surround condition. A dedicated study using isoluminant colours will be necessary to determine whether this pattern is robust.

The observed decrease of JND with age is consistent with prior studies suggesting that chromatic discrimination improves into early adulthood, reaches its highest levels around the third decade of life, and then gradually declines with further ageing [14, 21].

The surround luminances tested here, capped at 2000 cd/m^2 for participant comfort, are below the levels common in outdoor environments, where surface luminances readily reach 20 000–25 000 cd/m^2 [18]. The effects we report are therefore likely to be lower bounds on the impact of surround luminance under real-world bright conditions. Our follow-up work extends the current research in two complementary directions: an outdoor study assessing colour differentiability under natural viewing conditions, and a chromatic-differentiation study using isoluminant stimuli to characterize hue and chroma effects independently of lightness. Future work will also include an investigation of how the chromatic content of the surround, in addition to its luminance, affects colour differentiation in a mobile context.

8 Conclusion

Our study shows that surround luminance is a separable contributor to bright-environment SVIs on mobile displays, distinct from incident light reaching the screen. Cross-study analysis indicates that surround manipulation produces a JND-vs-illuminance slope approximately three times steeper than incident-illumination manipulation alone, and the effect concentrates at the bright end of the lightness scale, where mobile-outdoor use is most common. These findings, alongside the established perceptual literature on surround effects, argue for surround-aware extensions to mobile-display contrast guidelines. We are pursuing this direction through follow-up studies that will explore outdoor viewing conditions and chromatic differentiation.

Open Materials

The C-test software used in this study, along with documentation, is publicly available at https://gitlab.socs.uoguelph.ca/dnikiten/CTest. Subject to research ethics board approval, anonymized participant data will be released through the same repository.

Acknowledgments

We thank our participants for their help with this work.

References

[1] Ye Seul Baek, Hong-suk Kim, and Seung-ok Park. 2014. Determination of the Perceived Contrast Compensation Ratio for a Wide Range of Surround Luminance. *Journal of the Optical Society of Korea* 18, 1 (2014), 89–94. https://doi.org/10.3807/JOSK.2014.18.1.089

[2] C. J. Bartleson and E. J. Breneman. 1967. Brightness Perception in Complex Fields. *Journal of the Optical Society of America* 57, 7 (1967), 953–957. https://doi.org/10.1364/JOSA.57.000953

[3] Commission Internationale de l'Eclairage (CIE). 2004. *A Colour Appearance Model for Colour Management Systems: CIECAM02.* Technical Report CIE 159:2004. CIE Central Bureau, Vienna, Austria.

[4] Commission Internationale de l'Eclairage (CIE). 2022. *The CIE 2016 Colour Appearance Model for Colour Management Systems: CIECAM16.* Technical Report CIE 248:2022. CIE, Vienna, Austria. https://doi.org/10.25039/TR.248.2022

[5] EnChroma. 2022. Online ishihara colourblind test. https://enchroma.com/pages/test. https://enchroma.com/pages/test Accessed: May 21, 2026.

[6] David R. Flatla and Carl Gutwin. 2011. Improving calibration time and accuracy for situation-specific models of color differentiation. In *The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility* (Dundee, Scotland, UK) *(ASSETS '11)*. Association for Computing Machinery, New York, NY, USA, 195–202. https://doi.org/10.1145/2049536.2049572

[7] Chenyang Fu and M. Ronnier Luo. 2005. Methods for Measuring Viewing Parameters in CIECAM02. In *Proceedings of the 13th Color Imaging Conference.* 69–74. https://doi.org/10.2352/CIC.2005.13.1.art00013

[8] Rui Gong, Haisong Xu, Binyu Wang, and M. Ronnier Luo. 2012. Image quality evaluation for smart-phone displays at lighting levels of indoor and outdoor

conditions. *Optical Engineering* 51, 8 (2012), 084001. https://doi.org/10.1117/1.OE.51.8.084001

[9] Masoumehsadat Hosseini, Hamid-Reza Hamidi, and Shokooh Kermanshahani. 2024. The impacts of situational visual impairment on usability of touch screens. *Multimedia Tools and Applications* 83 (2024), 81685 – 81709. https://doi.org/10.1007/s11042-024-18689-9

[10] Youn Kim and Hong-Suk Kim. 2010. Spatial Luminance Contrast Sensitivity: Effects of Surround. *Journal of The Optical Society of Korea - J OPT SOC KOREA* 14 (06 2010), 152–162. https://doi.org/10.3807/JOSK.2010.14.2.152

[11] Peter Liu, Fahad Zafar, and Aldo Badano. 2013. The Effect of Ambient Illumination on Handheld Display Image Quality. *Journal of digital imaging* 27 (10 2013), 12–18. https://doi.org/10.1007/s10278-013-9636-1

[12] Kerr Macpherson, Garreth W. Tigwell, Rachel Menzies, and David R. Flatla. 2018. BrightLights: Gamifying Data Capture for Situational Visual Impairments. In *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility* (Galway, Ireland) *(ASSETS '18)*. Association for Computing Machinery, New York, NY, USA, 355–357. https://doi.org/10.1145/3234695.3241030

[13] Denis Nikitenko, Jordan Evans, David R. Flatla, Thomas Driscoll, Graham Quinlan, and Kyle Lukaszek. 2024. Situational visual impairments on mobile devices - modeling the effects of bright outdoor environments. In *Graphics Interface 2024 Second Deadline*. https://openreview.net/forum?id=OnoCcEANxD

[14] Galina V. Paramei and Beata Oakley. 2014. Variation of color discrimination across the life span. *Journal of the Optical Society of America A* 31, 4 (2014), A375–A384. https://doi.org/10.1364/JOSAA.31.00A375

[15] YungKyung Park, ChangJun Li, M Ronnier Luo, Youngshin Kwak, Du-Sik Park, and Changyeong Kim. 2007. Applying CIECAM02 for mobile display viewing conditions. In *Color and imaging conference*, Vol. 15. Society of Imaging Science and Technology, 169–173. https://doi.org/10.2352/CIC.2007.15.1.art00032

[16] YungKyung Park, ChangJun Li, M Ronnier Luo, Youngshin Kwak, Du-Sik Park, and Changyeong Kim. 2008. Testing colour appearance models for mobile phones using complex images. In *Color and Imaging Conference*, Vol. 16. Society of Imaging Science and Technology, 136–140. https://doi.org/10.2352/CIC.2008.16.1.art00027

[17] Katharina Reinecke, David R. Flatla, and Christopher Brooks. 2016. Enabling Designers to Foresee Which Colors Users Cannot See. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 2693–2704. https://doi.org/10.1145/2858036.2858077

[18] Javier Romero, Javier Hernández-Andrés, Juan Luis Nieves, and José A. García. 2003. Color coordinates of objects with daylight changes. *Color Research & Application* 28, 1 (2003), 25–35. https://doi.org/10.1002/col.10111

[19] Zhanna Sarsenbayeva, Niels Van Berkel, Weiwei Jiang, Danula Hettiachchi, Vassilis Kostakos, and Jorge Goncalves. 2019. Effect of ambient light on mobile interaction. In *Human-Computer Interaction–INTERACT 2019: 17th IFIP TC 13 International Conference, Paphos, Cyprus, September 2–6, 2019, Proceedings, Part III 17*. Springer, 465–475. https://doi.org/10.1007/978-3-030-29387-1_26

[20] Matthew Schuchhardt, Susmit Jha, Raid Ayoub, Michael Kishinevsky, and Gokhan Memik. 2015. Optimizing mobile display brightness by leveraging human visual perception. In *2015 International Conference on Compilers, Architecture and Synthesis for Embedded Systems (CASES)*. 11–20. https://doi.org/10.1109/CASES.2015.7324538

[21] Keizo Shinomori, Athanasios Panorgias, and John S. Werner. 2016. Discrimination thresholds of normal and anomalous trichromats: Model of senescent changes in ocular media density on the Cambridge Colour Test. *Journal of the Optical Society of America A* 33, 3 (2016), A65–A76. https://doi.org/10.1364/JOSAA.33.000A65

[22] Christopher Shooner and Kathy Mullen. 2020. Enhanced luminance sensitivity on color and luminance pedestals: Threshold measurements and a model of parvocellular luminance processing. *Journal of Vision* 20 (06 2020), 12. https://doi.org/10.1167/jov.20.6.12

[23] Garreth W. Tigwell, David R. Flatla, and Rachel Menzies. 2018. It's not just the light: understanding the factors causing situational visual impairments during mobile interaction. In *Proceedings of the 10th Nordic Conference on Human-Computer Interaction* (Oslo, Norway) *(NordiCHI '18)*. Association for Computing Machinery, New York, NY, USA, 338–351. https://doi.org/10.1145/3240167.3240207

[24] Garreth W. Tigwell, Zhanna Sarsenbayeva, Benjamin M. Gorman, David R. Flatla, Jorge Goncalves, Yeliz Yesilada, and Jacob O. Wobbrock. 2019. Addressing the Challenges of Situationally-Induced Impairments and Disabilities in Mobile Interaction. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/3290607.3299029

[25] World Wide Web Consortium (W3C). 2008. Web Content Accessibility Guidelines (WCAG) 2.0. http://www.w3.org/TR/WCAG20/