Situational visual impairments on mobile devices – modeling the effects of bright outdoor environments

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

Jordan Evans
University of Guelph
Guelph, ON, Canada

David R. Flatla
University of Guelph
Guelph, ON, Canada

Thomas Driscoll
University of Guelph
Guelph, ON, Canada

Graham Quinlan
University of Guelph
Guelph, ON, Canada

Kyle Lukaszek
University of Guelph
Guelph, ON, Canada

ABSTRACT

Mobile device users frequently experience Situational Visual Impairments (SVIs) when viewing screen content in bright outdoor environments. Designers could help alleviate SVIs if they had design tools that illustrated the effects that bright outdoor environments have on screen content. However, the exact nature of the underlying factors that lead to bright environment SVIs are poorly understood. To address this, we build on previous work by exploring the effects of bright environmental lighting on display content visibility using in-lab studies. In particular, we measured the differentiability of achromatic colours under a variety of realistic screen content and environmental brightnesses. Surprisingly, we found that environmental brightness makes a significant but relatively small contribution to reducing screen content visibility, with screen content brightness having a larger effect. As such, we conclude that non-glare ambient light reflecting off a screen has little influence on the visibility of that screen's content, and make recommendations for future research to help map the true factors underlying SVIs.

CCS CONCEPTS

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

KEYWORDS

HCI, accessibility, mobile computing, universal design

ACM Reference Format:
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 *Proceedings of Graphics Interface (GI24).* ACM, New York, NY, USA, 10 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

Mobile devices have become one of the primary ways in which we interact with the digital world. However, unlike regular computers, mobile devices are used in a wide variety of conditions that can sometimes hamper a user's ability to interact with their device.

One of the most common such conditions is when the screen content of a mobile device is difficult to see due to bright ambient lighting (e.g., using a mobile in bright sunlight) [31]. Such a condition is one common example of what are called Situational Visual Impairments (SVIs) [32].

In discussing mitigation strategies for such bright light SVIs, designers have called for new design tools to help them adapt their designs to these SVIs [29]. One approach to such a design tool would be to provide simulations of SVIs, such that designers could see how their designs appear to a user experiencing an SVI, much like simulations of Colour Vision Seficiencies (CVDs) are employed [16].

However, in order to provide design tool simulations of SVIs, a detailed understanding of exactly how bright light changes human visual perception is needed. Preliminary work in this space has shown that overall colour differentiability decreases with increasing environmental brightness or decreasing display brightness [23]. However, this early work: a) employed very dark screen brightness settings, b) used typical office ambient light levels rather than outdoor light levels, and c) did not vary the content brightness levels. In short, this preliminary work showed that SVIs are *measurable*, but did not provide the details we need to *simulate* SVIs.

To address this, we designed an in-lab study employing a modern mobile device at maximum screen brightness under a variety of ambient brightness levels ranging from dark to bright indirect daylight (the maximum brightness we could achieve with our experimental apparatus). We measured participants' achromatic colour differentiation abilities using a wide variety of screen content brightness levels.

In particular, our apparatus allowed us to measure the exact influence that ambient (or illuminant) light has on user ability to differentiate the brightness levels of screen content. In effect, we were measuring how incident bright light on a mobile screen influences how well users can tell individual screen content components apart.

We were surprised to find that, even at the brightest illuminant levels (32 500 lux), there was only a small but significant effect on screen content differentiability. We were more surprised to find that screen content brightness itself (i.e., how light the actual screen

---

GI24, June 03–06,2024, Halifax, NS

ACM ISBN 978-x-xxxx-xxxx-x/YY/MM
https://doi.org/XXXXXXX.XXXXXXX

content was) influenced content differentiability *more* than a four-magnitude change in illuminant brightness.

We make the following original contributions:

(1) A new analysis of previously collected data from a study [23] investigating participants' colour differentiation ability under different light conditions and screen brightness. In particular, we analyze whether increased difficulty of colour differentiation affects chromatic properties of colour, achromatic properties, or both.

(2) An analysis of the effect of ambient brightness levels on achromatic colour differentiation when the screen surround brightness is constant. This was done using a modern mobile device and three different in-lab studies that examined seven different screen brightness levels under six different ambient brightness levels (ranging from 1 lux to 32 500 lux) with 44 participants.

(3) A spectroradiometer-based analysis of the impact of ambient light ranging from 1 lux to 32 500 lux on the luminance (cd/m^2) and lightness (L^* value from CIE $L^*u^*v^*$ colour space) of the light reflected from a modern mobile device.

Our conclusion is that illuminant or environmental light (regardless of intensity) does not appear to substantially change the perception of on-screen content. Our study was focused on achromatic colours, however, we believe this also generalizes to the chromaticity of colours (i.e., our findings would be similar if we had employed content test colours varying in hue and chroma/saturation).

However, our study was carefully designed to exactly control for the amount of light coming from the environment *surrounding* the screen content – this never changed. The surprising results of our study have led us to conclude that future studies must explore the influence of very bright surroundings (something that is not addressed in current Colour Appearance Models), as potentially the key determiner of screen content visibility under SVI conditions.

2 RELATED WORK

2.1 SVIs and user interface design

In a world increasingly driven by mobile devices, SVIs are common and can cause issues completing tasks [15, 26, 32]. Furthermore, individuals can put themselves at risk trying to overcome an SVI to complete a task [25]. For example, struggling to see navigation directions in a car may distract the driver [25].

Examples of environmental factors contributing to SVI occurrences include bright environmental light, very low environmental light, changing light conditions, or the presence of a physical obstacle impeding the user's view [32]. Environmental factors can interact with other factors, worsening some while improving others, all of which complicates their study [17, 32].

Both hardware and software can contribute to SVI occurrences. Hardware factors include poor display quality or unstable battery power output. Software factors include features such as power-saving mode or blue-light filters. The severity of the SVIs may also be affected by the current position and angle of the device screen, relative to the user [30, 32].

The user interface design of mobile applications has been highlighted as a major contributing factor to SVI occurrences [26, 30]. Many designers do not test their designs for the mitigation of SVIs [31]. This could be due to lack of resources or a general misunderstanding of what SVIs are [31]. SVI-inducing factors that designers identify include using the design in bright light, the user wearing tinted glasses [6], and the user being far from the screen [31].

2.2 SVIs and colour perception / differentiation

One particular set of SVIs is caused by the effect of ambient light on both contrast and chromatic differences on different types of electronic screens [7, 9–11, 13, 23]. This has a negative effect on the users' ability to extract information and compete tasks using digital interfaces, as well as the overall perceived image quality [7, 9–11, 13, 24, 30]. While modern mobile display technologies have improved, they are still susceptible to SVIs in both bright and reduced ambient light [7, 13, 23, 24, 30]. In addition, while many modern operating systems have built-in adjustments that attempt to compensate for the effect of ambient illumination, they are not sufficient, and can sometimes become the cause of SVIs [30].

Some mobile device manufacturers do acknowledge the effect of environmental factors on colour appearance and legibility of screen elements in their HCI guidelines [8], but provide no specific design guidelines or tools aimed at mitigating bright light SVIs. Similarly, the Web Content Accessibility Guidelines contain no recommendations pertaining to the occurrence or mitigation of SVIs [35]. This may be due to the lack of ecologically valid data that could be used to inform such guidelines [15].

2.3 Simulating SVIs and CVDs for user interface developers

Tools that simulate vision impairments have been used to design accessible interfaces. This simulation software can recolour static images, as well as create transparent overlays that recolour interactive interfaces. However, such software typically focuses on congenital visual impairments, such as protanopia, deuteranopia, and tritanopia (all types of CVDs), and does not include SVI simulations [1, 5, 14, 16, 31, 33]. Providing such SVI simulations could help improve device accessibility [31]. Feedback from designers indicates interest in SVI software simulations that fit into the designers' typical workflow, allow for rapid development, and let designers select colour schemes themselves, instead of imposing an automated recolouring scheme [2, 29, 31, 34]. Such software would also help designers learn more about the needs of their users [2].

While it is known that bright light affects the human perception of contrast as well as colour discrimination ability [9, 11, 23], the exact effect of the bright illumination on colour appearance is not yet fully understood. This limits the ability of HCI researchers and designers to predict the appearance of different colours under specific illumination conditions, which makes it more difficult to design accessible interfaces. In addition, while different digital display types may have comparable characteristics under low light, they are also affected by bright light differently: AMOLED screens better preserve chromaticity, while IPS LCD screens help perception of brightness, contrast, and sharpness [7, 18]. As a result, software simulating colour appearance under bright illumination conditions may also need to account for different display types, in addition to modeling environmental factors.

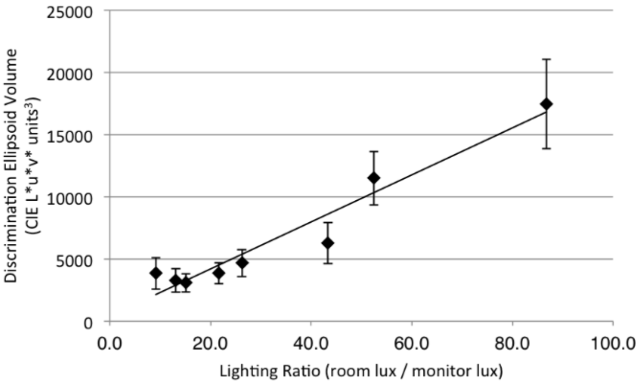

Figure 1: Mean discrimination ellipsoid volumes (in CIE L*u*v* units^3) ± s.e. for eight different lighting ratios. Copied from [23] with permission from one of the original authors.

Colour Appearance Models (CAMs) could potentially be applicable to this space, but the input parameters for CAMs are geared toward typical office environments, rather than the more extreme lighting conditions of outdoors [28]. Extending CIECAM02 to mobile has been explored [19–21], however, this work has yet to be adopted into a CIECAM standard.

3 PRELIMINARY DATA ANALYSIS

This work began with a re-analysis of the data collected by Reinecke, Flatla, and Brooks [23], whose study measured the effect of lighting – specifically, the lighting ratio (room lux/display lux) – on the participants' colour differentiation ability measured using discrimination ellipsoids [6, 22]. This data indicated that as the lighting ratio increased, the volume of discrimination ellipsoids also increased (see Figure 1). In other words, the participants had more trouble discriminating between colors as the viewing conditions became more difficult [23].

In order to better understand how to model the effect of the environmental conditions on colour differentiation – and, by extension, on visibility of display contents – we have re-analysed this data to investigate whether the increase in discrimination ellipsoid volume was due to:

- Increased difficulty of differentiating the chromatic properties of colour, which would manifest itself as the increase of the area of the discrimination ellipsoid along the u* and v* axes in the CIE L*u*v* colour space.
- Increased difficulty of differentiating lightness, i.e. increased height of the ellipsoid along the L* axis in the CIE L*u*v* colour space.
- Both of these factors.

Our analysis indicated that the increase in ellipsoid volume, which can be seen in Figure 1, was mostly due to the increase in area. The height of the ellipsoids, i.e. the difficulty of differentiating lightness, remained relatively consistent for all lighting ratios and increased only slightly, as can be seen in Figure 2.

Although these results suggested that achromatic colours do not contribute substantially to colour discrimination challenges related to SVIs, we were also cognizant of the limited ecological validity of the data on which we were relying (details below). As such, we opted to dive deeper into achromatic colour differentiation, both to more firmly establish its lack of contribution to SVIs, as well as to develop our evaluation procedure on a simpler dataset (achromatic colours occupy only a single 1D line of colour space, rather than the full 2D area of colours defined by hue and chroma).

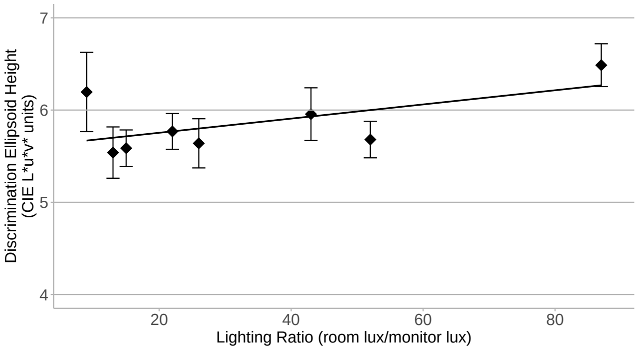

Figure 2: Mean discrimination ellipsoid heights (in CIE L*u*v* units) ± s.e. for each of eight lighting ratios.

4 COLOUR DIFFERENTIATION TESTS

The data re-analyzed above was collected using the following equipment and settings [23]:

- An LCD monitor set to relatively low brightness (12 - 69 lux, estimated using our calibration procedure to correspond to approximately 13 - 67 cd/m^2) was used to display the colour differentiation test.
- The content colour was always displayed at L*=50 in CIE L*u*v* units.
- The environmental brightness values were 629.5 lux and 1040.6 lux, which are far dimmer than most daytime outdoor lighting levels.

We conducted a series of empirical studies, referred to as Studies A, B, and C, to explore achromatic colour differentiation under conditions that more closely simulate mobile devices observed in outdoor settings. We selected achromatic colours as the starting point, because using them allowed us to use the process of elimination when investigating what factors contribute to the SVIs experienced by users in bright outdoor environments. Our subjective impression is also that the phone display simply looks darker in bright light. Therefore we investigated the effects of environmental brightness on visibility of achromatic display content, where chromatic properties of the content would not play a role.

Studies A-C were designed to measure the differentiation of achromatic colours in a dark environment, a bright indoor environment, and four different simulated outdoor environments. The experimental apparatus used in these studies was based on the C-test apparatus used to collect the preliminary data [23], which is described below in Section 4.2. The independent variables in Studies A-C were:

- Environmental brightness levels. Six different environments were investigated: three per study, as described in Section 4.1.
- Achromatic colours presented to the participants during the colour differentiation tasks. Seven achromatic colours were selected (Table 1, Section 4.2).

The dependent variable was the JND (just-noticeable distance) measured by our experimental apparatus to capture the participants' achromatic colour differentiation performance under the different environmental conditions and for the different achromatic colours.

4.1 Environments simulated by Studies A, B, C

Studies A and C used the following environmental illumination settings:

- 1 lux - this scenario represented a baseline viewing condition. There was no additional illumination on the screen, and the light within the apparatus was being emitted solely by the device display.
- 1500 lux - this scenario represented using a device in a bright indoor workspace, or outside during a dark overcast day.
- 27 500 lux - this scenario represented using a device in relatively bright indirect daylight on a clear day, or a very bright overcast day.

The conditions in study B were different and simulated only outdoor environments:

- 12 500 lux - this scenario represented mobile device usage in an overcast outdoor environment.
- 20 000 lux - this scenario represented mobile device usage in a partly cloudy outdoor environment.
- 32 500 lux - this scenario represented mobile device usage in bright indirect daylight. This was the brightest setting that our experimental apparatus could output in a stable manner.

All these environments were chosen to simulate realistic illumination contexts in which SVIs are known to occur [27, 36].

In studies A and B, participants were presented with each simulated environment in the order of increasing brightness. In study C, participants were presented with each simulated environment in the order of decreasing brightness in order to help control for potential ordering effects in the other studies.

4.2 Experimental apparatus

The experimental apparatus used for our study consisted of a mobile device housed within a large opaque box, which was used to simulate different environmental illumination levels. The center of the mobile device screen was visible through a circular aperture centered on the front of the box (see Figure 3). This aperture was meant to isolate the C-test from the environmental conditions in the lab. This isolation also reflected what the users might see in a hypothetical software-based SVI simulation, where the simulation would affect only the contents of the mobile device's screen.

A set of D65 LED light strips (99 CRI) was mounted on the inside of the wall containing the aperture (Figure 4) facing the mobile device. The LED light strips were controlled with an external dial, which allowed the experimenters to set the simulated environmental light incident on the mobile device. Participants completed achromatic colour differentiation tasks on the mobile device using an external numeric keypad.

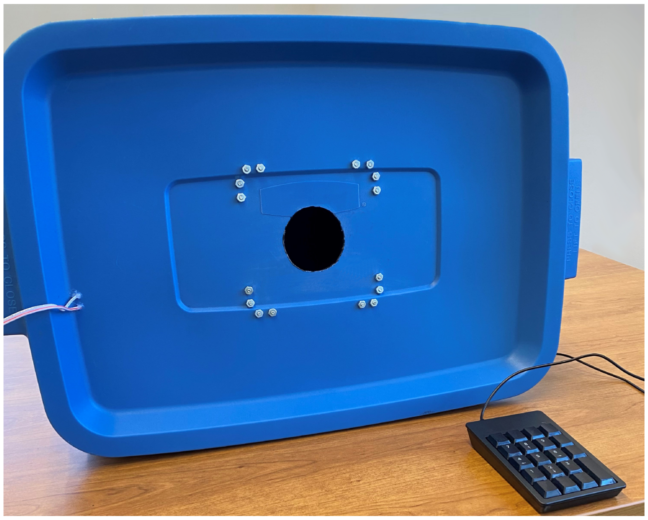

Figure 3: Full view of the C-test experimental apparatus.

The mobile device used for this study was an 11-inch iPad Pro tablet. Model A1980 was used for studies A and B. Due to technical issues, we had to switch to the 4th generation model A2759 for study C. Based on the available information, the two devices have similar screens and the same maximum brightness. Therefore we expected them to have similar colour reproduction capabilities and similar responses to environmental lighting.

The mobile device's native screen brightness was always set to 100% for all tested conditions. We chose the maximum device brightness to simulate a realistic scenario of a mobile display in an outdoor environment, since the majority of modern mobile devices automatically raise screen brightness when bright environmental light is detected. Additional display modes such as "true-tone" and "night-shift" were disabled, since they would introduce confounding factors by altering the appearance of the screen contents.

Four LED light strips were used to provide illumination within the environment. These strips were oriented in an overlapping "square" surrounding the aperture, with a width and height of 9cm, as shown in Figure 4. This orientation was chosen to provide an even diffusion of light across the center of the device screen. The lights were placed so that the reflections of the individual LED lights, or any other bright specular reflections (glare), could not be seen by the participants when looking through the aperture. The illumination produced by the light strips was measured using a light meter centered on the mobile device display facing the box aperture.

The software component of this apparatus, referred to as the "C-test" for brevity, presented a series of dynamically generated achromatic colour differentiation tasks using a center-surround visual field. Each trial of the C-test displayed a circle with a gap (resembling the letter "C") of a predefined achromatic test colour. The "C" was randomly oriented in one of eight possible directions (see Figure 5) and presented on a background of a different achromatic colour. The participants' task was to correctly identify the location

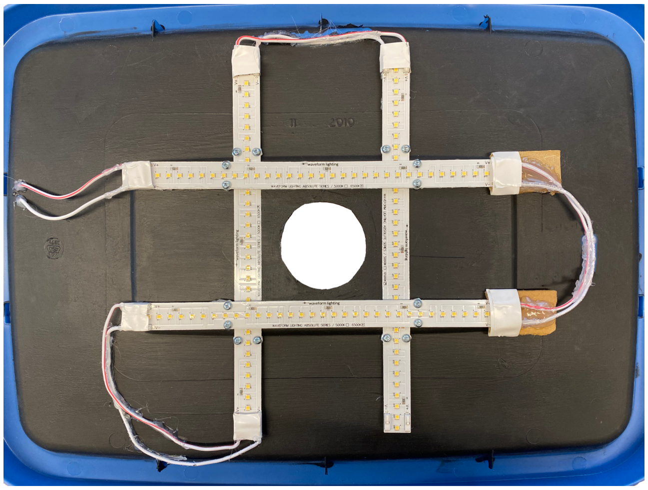

Figure 4: A view of the wiring and placement of LED strips within the C-test experimental apparatus.

of the gap in the “C” and press the corresponding button on the provided numeric keypad. If the participant was correct, the system considered the colour of the “C” and the colour of the background to be differentiable by the user. If the participant was incorrect or pressed the available “skip” button, the system considered the two colours not differentiable by the user.

This version of the C-test was an adaptation of the ICD-2 calibration task used in the creation of situation-specific models of colour vision deficiencies. This method was created as a way to build colour-differentiation models based on empirical data gathered from the user in the actual environment where the model will be deployed [4–6]. One benefit of ICD-2 over its predecessor ICD is that ICD-2 represents colour differences using the CIE L*u*v* colour model rather than the RGB colour model. Due to the perceptual uniformity of the CIE L*u*v* space, this allowed the same quantity of perceptual differentiation data to be collected using only eight measurements, compared with ICD’s 192 required measurements [4]. The ICD-2 method also yielded a more accurate calibration than the ICD method [4].

As may be seen by observing Figure 5 closely, foreground and background colours that were displayed were not uniform. They were also not static in a temporal sense. For each foreground and background luminance value, there was a range of luminance noise generated, so the background appeared to lightly flicker when viewed by the participants. This was done to reduce the effect of temporal adaptation on the participants’ luminance perception abilities [4, 6].

All three studies used the same seven achromatic test colours sampled evenly along the L* axis of the CIE L*u*v* colour space. The chosen test colours are listed in Table 1. Seven values were chosen, ranging from L* = 5 to L* = 95 in CIE L*u*v* units, to provide a wide sampling along the luminance axis. 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.

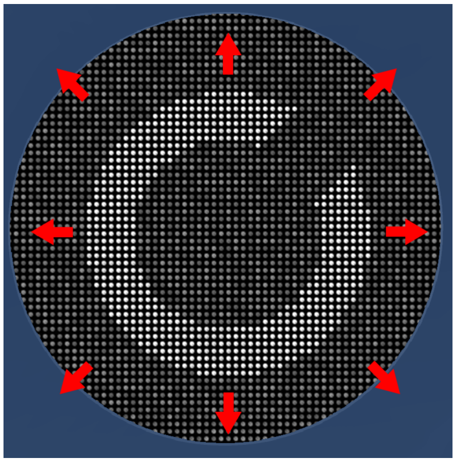

Figure 5: An example of a participant’s view through the aperture of the apparatus. The “C” could be oriented in one of the eight directions indicated by the red arrows. The participant identified the location of the gap by pressing the corresponding key on a numeric keypad. If the participant was correct, the foreground and background colours were considered differentiable for that trial.

Table 1: A list of achromatic colours selected as test colours for all conducted studies. The left column contains the luminance value of the test colour in CIE L*u*v* space. The middle column contains the approximate RGB conversion of each corresponding test colour, assuming the display’s sRGB gamut is calibrated to a white point of the D65 illuminant. The right column shows the corresponding colour.

CIE L*u*v* Test Colours	Approximate RGB values	Sample Colour patch
(5, 0, 0)	(17, 17, 17)	⬛
(20, 0, 0)	(48, 48, 48)	⬛
(35, 0, 0)	(82, 82, 82)	⬛
(50, 0, 0)	(119, 119, 119)	▨
(65, 0, 0)	(158, 158, 158)	▨
(80, 0, 0)	(198, 198, 198)	⬜
(95, 0, 0)	(241, 241, 241)	⬜

4.3 Participants

In total, 44 participants were recruited for the three studies described here:

- 16 participants were recruited for Study A. Nine were male and seven female, with the ages ranging from 19 to 29 years (mean age of 22 years).
- 16 participants were recruited for Study B. Five were female and 11 were male, with the ages ranging from 21 to 25 years (mean age of 22 years).

- 12 participants were recruited for Study C. Seven were male, four were female, and one non-disclosed, with the ages ranging from 18 to 24 years (mean age of 22 years).

All 44 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 [3].

4.4 Procedure

The studies were conducted in a lab with controlled light settings. All windows were covered by blinds and the room's ambient illumination was set to 300 lux, as determined by averaging five illumination measurements – four in the corners of the room and one at the participant location.

The participant location was centered in the room, with diffuse lighting positioned directly above it. There were no additional sources of light coming from behind the participants, or within the participants' field of view. The apparatus was placed on an adjustable desk with the aperture facing the participant's seat.

A chin rest to fix the participants' viewing angle and viewing distance was considered. However, studies A and B were conducted during COVID-19 lock-downs. Due to the risks involved with multiple participants' faces touching a shared surface, this option was excluded from the study design. Study C followed the same procedure for consistency.

Both the LED light strips and mobile device were turned on and set to maximum brightness at least 15 minutes prior to the start of each trial, to give 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 aperture and was orthogonal to the iPad Pro surface when they were sitting comfortably. The viewing distance was not fixed, but each participant's position was adjusted until their view angle was orthogonal to the screen and the view of the screen visible to them was as presented in Figure 5 – they could see the "C" and some background, and the "C" was centered in the aperture, but nothing else was visible (including glare from the LEDs). This setup is illustrated in Figure 6.

Each participant was given a 10-minute training session using the middle of the three illumination conditions that were being tested in each study.

After the training was complete, the simulated environment illumination was set to the desired intensity (verified with a light meter) and the participant conducted a single C-test session, which tested multiple achromatic colours under that illumination condition. In order to prevent eye strain, participants were encouraged to take breaks at any time by looking away from the apparatus.

Participants were also required to take at least a two-minute break before conducting the C-test at the next illumination condition, especially when switching from the 1500-lux environment to the 27 500-lux environment. This was done to prevent eye strain and to allow the experimenter to accurately adjust the apparatus LED strip brightness for the next simulated environmental setting.

5 RESULTS OF COLOUR DIFFERENTIATION TESTS

The results for each of the three studies consisted of three sets of just-noticeable distance (JND) measurements – one for each of the three environmental brightness settings explored by each study. For each environmental setting, the dataset contained seven subsets, one of each of the seven L* values. For each data set, data points outside the interval $[Q_1 - 1.5 \cdot IQR, Q_3 + 1.5 \cdot IQR]$ were treated as outliers and filtered out prior to model fitting, with Q_1 being the lower quartile and Q_3 the upper quartile. These outlier values were likely caused by participants' fatigue, boredom, or simply accidentally pressing the wrong key on the numpad when selecting the gap orientation of the "C".

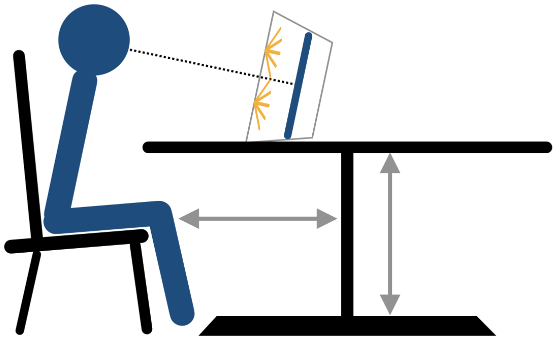

Figure 6: A diagram illustrating the the experimental setup and procedure. Desk height was adjusted for each participant to ensure a consistent view angle orthogonal to the screen. The lights were mounted on the inside of the lid and were invisible to the participant. The distance from the desk was adjusted to present the gapped circle, but avoid the glare from the LEDs on the iPad screen.

These results were analyzed by fitting a 2nd degree linear model to the JND data for each environmental setting, using the environment as the intercept. The adjusted R^2 values were 0.512 for the Study A model, 0.5246 for study B, and 0.6098 for study C. The R^2 values reflect the variability in the participants' responses, which can also be observed in the plots of the individual responses shown in Figures 7, 8, and 9.

The JNDs shown in Figures 7 and 8 increased overall for brighter achromatic colours, indicating that in every environment, the participants had greater difficulty differentiating brighter achromatic colours. However, the gaps between the models in each study were relatively small. These gaps represented the difference in the measured JND under various conditions, i.e. the differences in achromatic colour differentiation abilities in different environments. Wider gaps indicated larger differences in achromatic colour differentiation abilities.

Study A presented the participants with the darkest environment first (1 lux), and its results are shown in Figure 7. The environment had a statistically significant effect on the model: the model intercept increased by 0.33 CIE L*u*v units ($p < 0.01$) between 1 lux and 1500-lux environments, and 1.57 CIE L*u*v units between 1-lux and 27 000-lux environments ($p < 0.01$). This indicated that the JNDs for all three environments were statistically significantly different, indicating decreased differentiation of achromatic colour with a fairly small effect size. The JNDs for the 1-lux and 1500-lux environments were similar to each other in terms of effect size. The

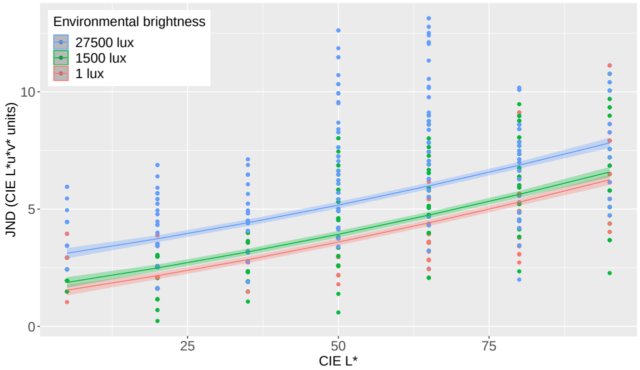

Figure 7: Summary of the data from Study A using a 2nd degree linear model (environmental brightness as intercepts, $R^2 = 0.512$).

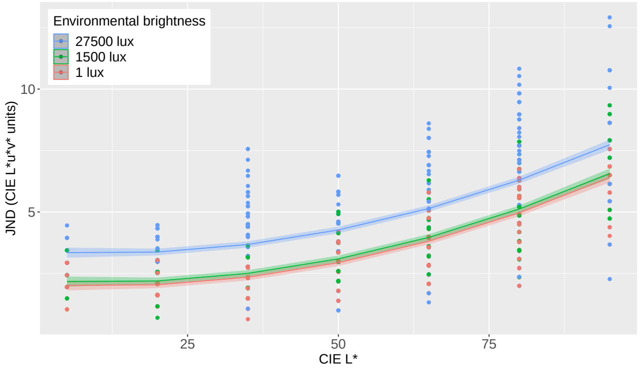

Figure 8: Summary of the data from Study C using a 2nd degree linear model (environmental brightness as intercepts, $R^2 = 0.6098$).

increase in JND caused by the brightest, 27 500-lux environment, was noticeable, but still fairly small. The screen content lightness had a larger effect on the achromatic colour differentiation ability.

Study C examined the same environments as study A, but presented them in the reverse order, starting with the brightest environment (27 500 lux). Its results are shown in Figure 8. These results were broadly consistent with study A. The 27 500-lux environment had a statistically significant effect on the model intercept, which increased by 1.33 CIE L*u*v units ($p < 0.01$). The significance of the 1500-lux environment was $p = 0.06$ and the model intercept increased by only 0.16 CIE L*u*v units (models for 1-lux and 1500-lux environments shown in Figure 8 almost completely overlap). This indicated that the JND for the 27 500-lux environment was significantly different from that of the 1-lux environment. These results also showed decreased differentiation of achromatic colour with a fairly small effect size, with the screen contents having a larger effect.

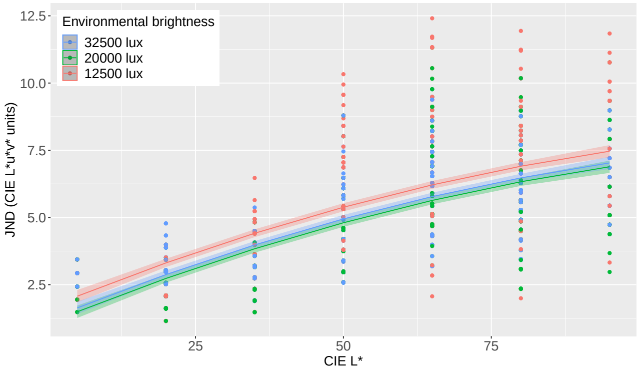

Figure 9: Summary of the data from Study B using a 2nd degree linear model (environmental brightness as intercepts, $R^2 = 0.5246$).

Study B examined three simulated outdoor environments, presented from darkest to brightest, and its results are shown in Figure 9. The JNDs for all three environments were significantly different ($p < 0.01$), though the JNDs for the 20 000-lux and 32 500-lux environments were similar to each other in terms of effect size. Intercept difference was -0.57 CIE L*u*v* units between 12 500 and 20 000-lux and -0.43 CIE L*u*v units between 12 500 and 32 500 lux (models for 20 000-lux and 32 500 lux shown in Figure 9 almost completely overlap). The results of study B therefore indicate that the JND decreased for brighter environments and this decrease was statistically significant, although relatively small in terms of effect size. These somewhat unexpected findings are discussed in the next section. As in Studies A and C, the effect of the screen content lightness was larger than that of the environmental brightness.

In addition, we have examined the effect of the lighting ratio (environmental lux/display lux) on the JND, as was done in our initial analysis. While studies A-C used much brighter environments than the earlier study, the display was also significantly brighter, and the overall lighting ratios were similar.

First-degree linear models for these results are shown in Figure 10. All the intercepts were statistically significantly different from L*=5 ($p < 0.01$), with the exception of L* = 20 (the models for L*=5 and L*=20 overlap in Figure 10), showing a significant impact of screen content lightness on achromatic colour differentiability. They also show that the JND increased as the light ratio increased – and the viewing conditions became more challenging – but the effect was small and the increase was gradual. This was consistent with the relationship observed in the initial analysis, shown earlier in Figure 2, but with the added results pertaining to different screen content lightnesses.

6 SPECTRORADIOMETER TESTS

In any environment with light sources other than the screen, the light observed by the user when viewing the screen is a combination of the light emitted by the screen and environmental light reflected by the screen. Therefore the light in the environment can potentially affect both the luminance and chromatic properties of the screen contents.

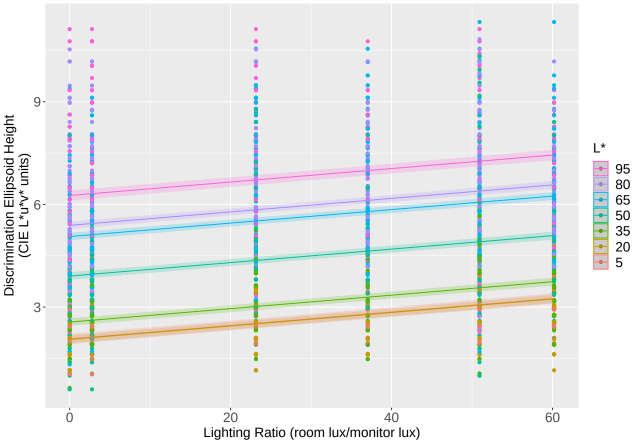

Figure 10: Linear model JNDs (in CIE L*u*v* units) ± s.e. for each of eight lighting ratios (1st degree linear models using L* as intercepts, $R^2 = 0.54$).

Table 2: A summary of our spectroradiometer measurements. All luminance values are in cd/m^2. "Ref. L*" are L* values from CIE L*u*v* colour space displayed on the screen; "L_v" and "Rec. L*" are the luminance and L* values recorded by the spectroradiometer, respectively. All results shown here are rounded to the nearest integer value for clarity and brevity.

Ref. L*		Environmental light levels (lux)					
		1	1500	12 500	20 000	27 500	32 500
5	L_v	2	2	7	9	11	12
	$Rec.\quad L*$	7	10	17	19	21	22
20	L_v	13	17	30	32	32	33
	$Rec.\quad L*$	23	26	33	34	34	34
35	L_v	42	44	56	59	57	57
	$Rec.\quad L*$	38	39	43	44	43	43
50	L_v	97	97	112	115	110	108
	$Rec.\quad L*$	53	53	56	57	56	56
65	L_v	179	182	208	211	203	199
	$Rec.\quad L*$	67	68	71	72	71	70
80	L_v	296	300	344	348	339	335
	$Rec.\quad L*$	81	82	86	86	85	85
95	L_v	455	464	532	539	527	524
	$Rec.\quad L*$	96	96	100	100	100	100

As such, we also investigated the impact of the environmental light reflected off the screen on the screen brightness and the achromatic colours visible to the participants using a spectroradiometer. We used the JETI spectraval 1501 spectroradiometer, positioned in front of the C-test apparatus and aimed at the portion of the device screen visible through the aperture. We displayed the seven achromatic colours listed in Table 1, under the six environmental brightness settings used in Studies A through C, so this set of measurements had the same independent variables as the studies described in Sections 4 and 5. We used the spectroradiometer to record the luminance (in cd/m^2) and the L* value from CIE L*u*v* colour space, which served as dependent variables.

The results are summarized in Table 2. The L* values reported by the spectroradiometer were scaled to the [0,100] range. The minor discrepancies between the reference L* and recorded L* values at 1 lux can be explained by the colour reproduction limitations of the display used in the study.

As can be seen from Table 2, reflected light did contribute to the brightness of the screen observed by the participants. However, this effect was relatively small. The luminance increases ranged from 10 cd/m^2 for L*=5 to 69 cd/m^2 for L*=95.

In addition, Table 2 also showed an increase in measured L* values, which happened primarily as the environmental brightness was increased from 1 lux to 12 500 lux. This was most pronounced for darker colours. For example, the measured L* values increased from 7 to 22 CIE L*u*v* units for reference L*=5, but the increase was from 96 to 100 CIE L*u*v* units for reference L*=95.

The chroma values recorded by the spectroradiometer remained relatively consistent in all simulated environments, although a small colour shift was observed. Since our paper focuses on achromatic colours, these results are not discussed here. We will investigate the effect of environmental light on the differentiability of chromatic colours and its impact on screen content visibility in future work.

7 DISCUSSION

Results from studies A-C (Figures 7 - 10) were all broadly consistent with our initial analysis (Figure 2). The observed effect of ambient illumination on achromatic colour differentiation was relatively small, although it was statistically significant. The effect was similar to the results observed in our initial analysis. The JND typically increased somewhat as the viewing conditions became more difficult, indicating decreased visibility of screen contents, but the effect was small and the increase was gradual. More surprisingly, the magnitude of the JND observed in Studies A - C depended on the colours being shown.

Studies A and C showed that achromatic colour differentiation ability decreases as environmental brightness increases, as would be expected. This happened regardless of whether our participants experienced a darker or a lighter environment first, and the severity of the SVIs experienced by the participants under the brightest environmental condition was similar in both settings.

Study B showed that the achromatic colour differentiation abilities of the participants slightly improved as they were presented with increasingly brighter simulated outdoor environments (12 500 lux , 20 000 lux, and 32 500 lux), which was unexpected. However, all three environments in Study B ended up modeling relatively similar conditions: different degrees of indirect sunlight on a clear day, or a bright overcast day [12]. We hypothesise that we observed the results of temporal adaptation by the participants. Each participant's visual system continued to successfully adapt to relatively similar conditions as the study progressed, leaving achromatic colour differentiability unaffected and even slightly improved as time progressed. This effect was not observed for studies A and C, where the three simulated environments – a dark environment (1 lux), a bright indoor environment (1500 lux), and a relatively bright outdoor environment (27 500 lux) – were all fundamentally different from each other.

Overall, our most surprising finding was that the impact of environmental brightness on achromatic colour differentiation was smaller than may have been expected. One contributing factor may have been the technical limitations of the apparatus. Bright, direct sunlight can result in illuminance of over 100 000 lux [12], which exceeds the maximum brightness achievable by our experimental apparatus. These light levels might be difficult to obtain in the lab settings without causing discomfort to the participants and may require follow-up studies in outdoor settings. Our experimental apparatus was also designed to eliminate bright specular reflections (glare), while such reflections undoubtedly occur in outdoor settings and are expected to contribute to SVIs.

More importantly, our apparatus illuminated the mobile display, but not the background surrounding it – the aperture was designed to leave only the section of the mobile device showing the C-test visible to the participants. This may have helped our participants retain their colour differentiation abilities even when the display was lit by increasingly brighter light, since the area surrounding the brightly lit display remained relatively dark.

On the other hand, when a mobile device is viewed in realistic outdoor conditions, the display screen occupies a relatively small area of the observer's field of view. It is surrounded by other objects in the observer's environment – the ground, buildings, vegetation, etc.. The colour and brightness of the elements in the surrounding environment contribute to the observer's perception of the colours on the screen. In a sufficiently bright outdoor environment, the light reflected from the background might be brighter than the combination of the light emitted and reflected from the screen, and the observer may be viewing the mobile device as a relatively dark object on a light background. As a result, we think that the display surround was a factor that significantly affected our findings.

An illustration from recent events is potentially useful here for illuminating our conclusion. The 2024 North American solar eclipse caused many people to experience a rapid swing in illumination (i.e., sunlight) levels. As the sky darkened, non-automatic artificial lights in the environment (e.g., front lights on houses, car lights) were perceived to get increasingly brighter, even though on a regular day people might not even notice them. However, the total amount of light coming from these sources remained constant throughout the eclipse.

Our SVI situation is much like these artificial lights. The total amount of light from a mobile device screen is limited by the maximum brightness of the screen, modulated by the lightness of the screen content itself. However, the total amount of light coming at the user from the area *around* their phone can be much higher than that produced by the mobile screen itself.

For example, consider using a mobile standing out in the sun. At one angle, the mobile's "surround" is a field of bright winter snow, but at a slightly different angle, the mobile's "surround" is the shadow under a tree. The total light coming from the device will be the same and the total amount of sunlight shining on the device's screen is the same, but the light reflected from the snow drowns out the display content, whereas the light from the shadow does not.

Future studies will need to investigate the effect of the surrounding environment, especially in bright light, on the visibility of screen content and differentiability of both chromatic and achromatic colours. If the background surrounding a mobile device plays a significant role in inducing SVIs, as we hypothesize, then simulation software would need to take this into account. The parameters of the simulation would have to include not only the environmental brightness settings, but also the various backgrounds for the mobile device. The simulated output itself may also need to include not only the device screen, but also the surrounding background environment.

8 CONCLUSION

In summary, we have investigated the effect of outdoor illumination on achromatic colour differentiability. Our findings indicate that the light falling on the screen or being reflected from the screen is not the most significant contributor to SVIs under the conditions investigated in our study. Our results point to other factors, such as the surrounding environment, as potentially contributing more strongly to the SVIs experienced by mobile device users in bright environments. Identifying and modeling all of these significant factors will help us build accurate SVI simulations and create more accessible mobile interfaces.

ACKNOWLEDGMENTS

We thank our participants, as well as Andrew Hamilton-Wright and Stacey Scott for patiently sharing the lab with us while we ran our studies.

REFERENCES

[1] Hans Brettel, Françoise Viénot, and John D Mollon. 1997. Computerized simulation of color appearance for dichromats. *Journal of the Optical Society of America. A, Optics, image science, and vision* 14, 10 (1997), 2647–2655. https://api.semanticscholar.org/CorpusID:5737802

[2] Michael Crabb, Michael Heron, Rhianne Jones, Mike Armstrong, Hayley Reid, and Amy Wilson. 2019. Developing Accessible Services: Understanding Current Knowledge and Areas for Future Support. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300446

[3] EnChroma. 2022. Online ishihara colourblind test. https://enchroma.com/pages/test. https://enchroma.com/pages/test

[4] 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

[5] David R. Flatla and Carl Gutwin. 2012. "So that's what you see": building understanding with personalized simulations of colour vision deficiency. In *Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility* (Boulder, Colorado, USA) *(ASSETS '12)*. Association for Computing Machinery, New York, NY, USA, 167–174. https://doi.org/10.1145/2384916.2384946

[6] David R. Flatla and Carl Gutwin. 2012. SSMRecolor: improving recoloring tools with situation-specific models of color differentiation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 2297–2306. https://doi.org/10.1145/2207676.2208388

[7] 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

[8] Apple Inc. 2024. Apple Developer Documentation - Human Interface Guidelines - Foundation - Color. https://developer.apple.com/design/human-interface-guidelines/color. https://developer.apple.com/design/human-interface-guidelines/color

[9] 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

[10] Youn Kim, Ming Luo, Wonhee Choe, Hong Kim, Seung Park, Yeseul Baek, Peter Rhodes, Seongdeok Lee, and Chang Yeong Kim. 2008. Factors affecting the

psychophysical image quality evaluation of mobile phone displays: The case of transmissive liquid-crystal displays. *Journal of the Optical Society of America. A, Optics, image science, and vision* 25 (10 2008), 2215–22. https://doi.org/10.1364/JOSAA.25.002215

[11] Youn Jin Kim, M Ronnier Luo, Peter Rhodes, Vien Cheung, Stephen Westland, Seungsin Lee, Youngshin Kwak, Dusik Park, and Chang Yeong Kim. 2007. Measurement of perceived brightness and contrast sensitivity for outdoor condition. *Proceedings of the 26th Session of the Commission International de L'Eclairage, Beijing, China* (2007), 1–4.

[12] Stelios Kouridakis and Panagiotis Giakoumakis. 2020. Electronic device design for energy harvesting of indoor and outdoor light sources for multiple low power usage. *International Journal of Circuits and Electronics* 5 (2020), 49–54.

[13] 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). https://doi.org/10.1007/s10278-013-9636-1

[14] Gustavo M Machado, Manuel M Oliveira, and Leandro AF Fernandes. 2009. A Physiologically-based Model for Simulation of Color Vision Deficiency. *IEEE Transactions on Visualization and Computer Graphics* 15, 6 (2009), 1291–1298. https://api.semanticscholar.org/CorpusID:6200253

[15] 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

[16] Rhouri McAlpine and David R. Flatla. 2016. Real-Time Mobile Personalized Simulations of Impaired Colour Vision. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility* (Reno, Nevada, USA) *(ASSETS '16)*. Association for Computing Machinery, New York, NY, USA, 181–189. https://doi.org/10.1145/2982142.2982170

[17] Ján Morovič. 2008. *Color Gamut Mapping* (1st ed.). Wiley. 286 pages.

[18] Tae-Yong Park, Jun Woo Jang, Kwang-Hoon Shin, Jang Jin Yoo, and Hyun-Ho Shin. 2011. P-42: Evaluation of the Ability to Reproduce Preferred Colors for Mobile Displays under Ambient Illumination Condition. *SID Symposium Digest of Technical Papers* 42, 1 (2011), 1253–1256. https://doi.org/10.1889/1.3621061

[19] YungKyung Park, ChangJun Li, M Ronnier Luo, Wonhee Choe, Seongdeok Lee, and Changyeong Kim. 2006. Colour appearance modelling for mobile displays. In *Color and Imaging Conference*, Vol. 14. Society of Imaging Science and Technology, 18–23.

[20] 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.

[21] 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.

[22] Allen Poirson and Brian A. Wandell. 1990. The ellipsoidal representation of spectral sensitivity. *Vision Research* 30 (1990), 647–652. https://api.semanticscholar.org/CorpusID:42722616

[23] 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

[24] 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

[25] Sidas Saulynas and Ravi Kuber. 2018. Towards Supporting Mobile Device Users Facing Severely Constraining Situational Impairments. In *CHI EA '18: Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–6. https://doi.org/10.1145/3170427.3188642

[26] Andrew Sears, Min Lin, Julie Jacko, and Yan Xiao. 2003. When Computers Fade... Pervasive Computing and Situationally-Induced Impairments and Disabilities. *HCI international* 2 (2003), 1298–1301. Issue 3.

[27] James V. Stone. 2012. *Vision and Brain: How We Perceive the World* (illustrated ed.). The MIT Press.

[28] Maureen C. Stone. 2003. *A Field Guide to Digital Color*. A. K. Peters, Natick, Massachusetts, USA.

[29] Garreth W. Tigwell. 2019. *Improving Content Design on Mobile Devices to Reduce Situational Visual Impairments*. Ph. D. Dissertation. University of Dundee.

[30] 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

[31] Garreth W. Tigwell, Rachel Menzies, and David R. Flatla. 2018. Designing for Situational Visual Impairments: Supporting Early-Career Designers of Mobile Content. In *Proceedings of the 2018 Designing Interactive Systems Conference* (Hong Kong, China) *(DIS '18)*. Association for Computing Machinery, New York, NY, USA, 387–399. https://doi.org/10.1145/3196709.3196760

[32] 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

[33] Radu-Daniel Vatavu. 2017. Visual Impairments and Mobile Touchscreen Interaction: State-of-the-Art, Causes of Visual Impairment, and Design Guidelines. *International Journal of Human–Computer Interaction* 33 (2017), 486 – 509. https://api.semanticscholar.org/CorpusID:45094797

[34] Francoise Vienot, Hans Brettel, and John D Mollon. 1999. *Digital video colourmaps for checking the legibility of displays by dichromats* (4 ed.). Vol. 24. John Wiley & Sons, Ltd. 243–252 pages.

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

[36] Günter Wyszecki and W. S. Stiles. 1982. *Color Science: Concepts and Methods, Quantitative Data and Formulae* (2nd ed.). Wiley. 950 pages.