

# Towards Calm Displays: Matching Ambient Illumination in Bedrooms

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We present a system for making emissive computer displays (LCDs) look like they are reflective, i.e. not emitting light but instead reflecting ambient light, an effect that we call a “calm display”. We achieve this effect by using a light sensor and a one-time calibration process to drive an algorithm which controls the display’s backlight intensity and gamma correction functionality to continually match the brightness and chromaticity of the ambient light. We present an experimental evaluation of our system, showing quantitatively that the color and brightness output by our system is perceptually close to that of a piece of paper under similar lighting conditions. We argue that calm displays can more easily fade into the background, and further that they are more suitable for environments such as bedrooms where glowing displays are often out-of-place. We validate these claims and more generally explore users’ perception of calm displays, through a field study of an LCD display deployed in participants’ bedrooms.

CCS Concepts: • **Human-centered computing** → **Ubiquitous and mobile computing**

General Terms: Design, Algorithms, Performance

Additional Key Words and Phrases: displays; calm technology; ambient displays; picture frames; RGB sensors; color perception; negative brightness

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## 1 INTRODUCTION

Displaying information in the environment has been shown to be an effective way of supporting multi-tasking [1], improving awareness [2, 3] and providing reminders [4]. However, to avoid information overload, Weiser and Seely Brown noted that it was important for these information sources to be “calm”: displays must be able to easily move from the center of attention to the periphery and back [3].

Light-emitting LCD or OLED panels are often used when implementing the environmental displays described above because they are high resolution, highly dynamic, low-cost, and can be easily controlled using computers. However, a major problem with using these panels is that they emit light independently from ambient illumination. This is in sharp contrast to other objects in the environment like walls, furniture and photographs, which are reflective and change appearance depending on the ambient illumination. The mismatch in brightness and chromaticity (hue) draws unwanted attention and compromises the ability of devices employing these panels to calmly fade into the periphery.

In this paper we tackle the problem of display panels being environmentally intrusive as a result of brightness and chromaticity mismatches. We present a new system combining sensing hardware and algorithms for dynamically adjusting the output of emissive displays so that they respond to ambient illumination. The end effect is that content behaves as if it is printed on non-emissive media such as paper. Our method uses low-cost, commodity RGB sensors rather than expensive calibrated colorimeters or cameras. It is also fast and stable, responding to illumination changes in real-time with few visual artefacts. To validate our method and evaluate its performance, we conducted an experiment comparing the appearance of a display running our algorithm against paper, under various lighting conditions, using the methods of colorimetry.

To test whether our ambient light-matching technique reduces environmental intrusiveness under real-world lighting conditions, we set up tablet computers as always-on situated displays in the bedrooms of 10 participants over a two-week period. For one week, the tablets used the display's normal adaptive backlighting system and during the other week, the same devices used the light-matching system described in this paper. Overall, participants reported that the devices using our system were less distracting and more appropriate for the bedroom. Device logs further showed that participants switched off the non-matched devices nearly every night, while the lighting-matched devices were rarely switched off manually. The reduced distraction came at the cost of slightly lower ease of viewing.

The different behaviors observed and the qualitative responses of our study participants showed that our design and implementation of the light-matching technique has gone some way towards achieving "calm" displays, and also pointed towards further improvements and applications for such displays.

## 2 RELATED WORK

### 2.1 Information Displays in the Periphery

The ability to present information in a way that is more environmentally integrated has been a long-sought goal in the ubiquitous computing domain. Pousman and Stasko refer to "ambient information systems" and their taxonomy of devices [5] provides many examples of work in the domain. A key common element across these efforts is the transition between users' periphery and focus of attention and back. By doing so, these displays are examples of what Weiser and Seely Brown term "calm technology." That these displays fade into the background is critical: Mankoff et al. [6] report that an ambient display's ability to move into the periphery was judged to be the most relevant factor in its usability.

A large number of ambient information systems in the literature have been built around commodity display panels [7, 8, 9, 10]. In some of these systems, light emission has been shown interfere with the displays' ability to fade into the background. For example, Consolvo et al. reported that the glow from the CareNet display they deployed disturbed users who were in bed or trying to watch TV [7]. In response to user feedback, Consolvo et al. proposed that their ambient display should automatically dim in response to ambient illumination. Given the decreasing cost of display panels and mobile computing hardware and growing prevalence of intelligent devices in the home, we anticipate that environmental intrusiveness due to illumination will become increasingly problematic.

### 2.2 Color Matching

Color matching, i.e. the ability to recreate observed colors, is required across fields as diverse as car manufacture [11], fashion [12], industrial design [13], dentistry [14] or augmented reality [15, 16, 17]. The closest color matching task related to our work is the color appearance modeling [18], which predicts how an image or color will appear under various lighting conditions. The digital content is then modified so that it appears on the display as it would in the modeled environment, assuming the display is under strictly defined viewing conditions. The difference with our system is that we adjust the display properties to target highly variable viewing conditions, relaxing the requirement on a colorimetric match to a specific reference image. This allows the display to blend into the background enough to decrease the distracting nature of displays.

### 2.3 Responding to Ambient Illumination

Presently, the main motivation in the literature for sensing ambient light is to enhance the display on devices occupying the center of a user's attention. Adaptive backlighting and color corrections have been employed to improve users' viewing experiences [19, 20, 21]. In the commercial space, f.lux<sup>1</sup> is a popular application for adjusting the color temperature of the display based on location and time of day but not actual lighting

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<sup>1</sup> <http://justgetflux.com/>



Fig. 1. Eight photos of our test setup, each taken under different colored and brightness ambient lighting conditions. In each photo the calm display (top left) adapts to the lighting in a similar way to paper (bottom left). Common adaptive display brightness (top right) and a calm display without color corrections (bottom right) are shown for comparison.

conditions. Apple's TrueTone feature in new iPads employs two light sensors and alters the display to improve color accuracy and improve readability. Although these efforts adjust luminance and color of the display in response to external lighting conditions, they are targeted to displays that are being directly attended to, rather than peripheral displays. In the iPad case, since it is battery powered, when the device determines it is not in active use, it goes quickly into low power mode – not calmly fading into the periphery, but becoming dormant.

A smaller set of projects feature peripheral displays adapting to match ambient illumination. The Video Window [22] was an early implementation of a display that coarsely responded to ambient illumination by mirroring the view from a camera mounted outside the house. The fact that the Video Window was responsive to illumination may partially explain why Gaver did not find the device disruptive in the bedroom.

More recently, Bavor [23] blogged about a home-built system making a light emitting screen look like reflective media by using photodiodes to match luminance. In Bavor's implementation, only the luminance is taken into account and color adjustments are hard-coded. Moreover, the calibration must be performed on a per-environment basis and it was only tested in that single environment. In contrast, our technique requires a single, environment-independent calibration step and performs brightness as well as color corrections. We also provide more comprehensive details about the hardware and software implementation.

Finally, reflective display technologies, like e-paper, are able sidestep the problem of illumination mismatch. However, there are significant tradeoffs when using these alternative display technologies. E-paper, in particular, suffers from slower refresh speed, poor color reproduction, and higher cost when compared to LCD and OLED panels.

### 3 AMBIENT ILLUMINATION MATCHING

The overall aim of our algorithm is to adjust the output of standard liquid crystal display (LCD) panels found in many devices to match the amount of light (brightness) and chromaticity (hue and saturation) that a reflective surface, such as paper, would reflect when showing the same image (see Fig. 1). On the input side our system uses an RGB light sensor to measure the brightness and chromaticity of ambient light. At the output end, our system relies on modifying gamma correction curves in the display adapter and adjusting backlight intensity to control display output.

A one-time calibration procedure must be run to determine the characteristics of the RGB sensor and display panel. After this initial calibration step, our algorithm (Fig. 2) uses the RGB sensor values to compute two parameters that specify how to adjust the display. The first of these is a set of three gamma scaling factors (one for each color channel) that are multiplied to the system gamma curves to adjust chromaticity. The other parameter is a backlight intensity value to control brightness. In bright conditions, chromaticity and brightness

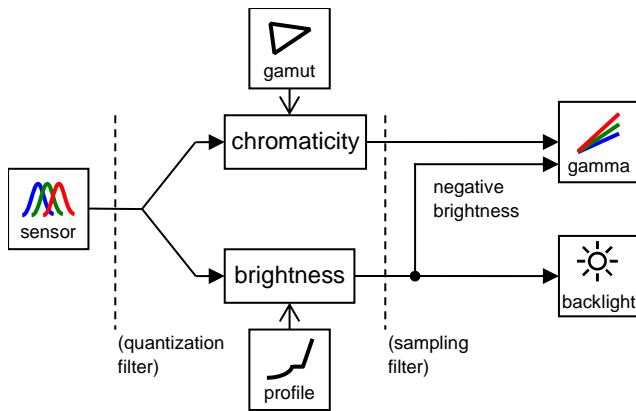


Fig. 2. Schematic overview of our algorithm.



Fig. 3. Custom-built USB dongle with 4-channel (RGB+clear) TCS43275 light sensor.

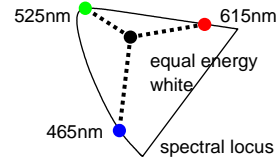


Fig. 4. RGB sensor pseudo primaries.

matching occur independently. However, when the desired brightness is lower than the lowest backlight setting, the gamma scaling factors are further adjusted to achieve this lower brightness.

### 3.1 Hardware

Many inexpensive, off-the-shelf RGB sensors can be used in our system. In first prototypes, we found that the only critical requirement was that all color channels are read simultaneously, i.e. each sensed channel should have its own analog to digital converter (ADC). Sensors with only a single ADC report invalid color readings during lighting changes, resulting in noticeable flickering artifacts. In our prototype, we used TCS 43725 sensor<sup>2</sup> made by ams AG for around 4 USD. This sensor has RGB channels as well as a clear channel for overall illuminance. We integrated the sensor into a custom PCB and 3D printed case, with an MSP430 processor presenting the sensor data over a USB interface, as shown in Fig. 3.

The sensor readings need to be converted to an additive space where colors can be linearly interpolated. Our system uses the CIE 1976  $u'v'$  chromacity space [24] due to its perceptual uniformity. Since any perceptual color space needs to be based on human vision response, there is no well-defined mapping from various responses of common RGB sensors into those spaces. Sensors that match the human vision characteristics exist, but they are more expensive and current technology allows only for a very narrow sensing angles.<sup>3</sup>

However, our algorithm is not concerned about the absolute colorimetric values of the color sensed, but only about the color's relative position in the color space with respect to the sensor's absolute limits. In order to transform RGB values to the  $u'v'$  chromacity diagram, coordinates for red, green and blue primaries are needed. We use the pure colors on the chromaticity diagram's spectral locus corresponding to the peak sensitivity of each of the sensor's channels (615nm, 525nm resp. 465nm) as the primaries, as shown in Fig. 4. This space will be referred to as the  $\hat{u}'\hat{v}'$  space as the values are not true  $u'v'$  colors in the CIE sense.

### 3.2 Calibration

Calibration data are required for both chromaticity matching and brightness matching. Note that the calibration is only required a single time for each combination of: model of sensor, mounting of sensor (including diffuser), and model of display panel. In other words, the variation between individual display panel units or sensor units

<sup>2</sup> <http://ams.com/eng/Products/Light-Sensors/Color-Sensors/TCS34725>

<sup>3</sup> <http://www.mazet.de/en/products/jencolor/true-color-sensors.html>

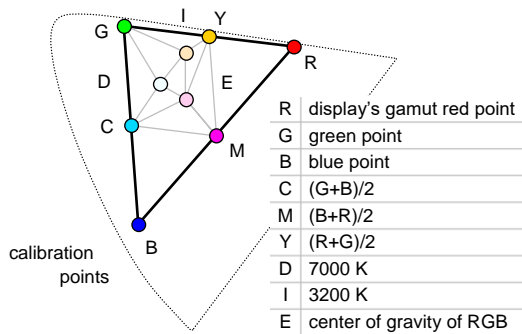


Fig. 5. Chromaticity calibration data in the  $u'v'$  space.

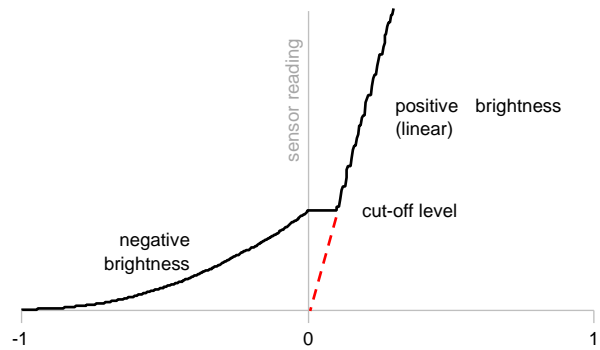


Fig. 6. Brightness calibration data, including “negative brightness” lower than the minimum backlight level, achieved by using gamma tables to further dim the display

of the same model is not enough to affect calibration significantly, hence different devices of the same type can all share a single calibration. We implemented software automating all the calibration steps described below into a step-by-step process.

**3.2.1 Chromaticity calibration.** Chromaticity calibration data consists of the desired display outputs for a set of given sensor readings. The algorithm then interpolates display output from the known points.

In our prototype, we use a calibration matrix that includes the extremes of the display gamut (i.e. the  $u'v'$  coordinates of the red, green and blue primaries of the display) and several points on the triangle that it forms, as well as several points close to the white point, as depicted in Fig. 5.

The coordinates of the points in Fig. 5 represent the sensor readings transformed into the  $u'v'$  space as described above, and the colors of the points show the desired display output.

The calibration data can be acquired using configurable lighting. For each calibration point we set the illumination to have the specified color, sense this electronically, and manually adjust the display settings so that when it displays a white screen, the output matches the color of a white paper reference. In our setup, we used Philips Hue lights to set the ambient lighting conditions (model LLC010, swversion 66013452) and Xerox Digital Paper (PW) (wrapping reference 003R94779). The lights were on a desk 55cm away from the sensor/paper/display.

**3.2.2 Brightness calibration.** For brightness calibration, we need to obtain the display’s brightness profile. This can be acquired by placing an RGB sensor directly on the display surface, and recording clear-channel sensor readings for various brightness levels of the display.

Fig. 6 shows a typical brightness profile (to the right of “0”). The built-in backlight control provides linear control of the brightness, but only down to a *cut-off level*, a brightness value for which any lower requested value results in the same display output. This is because on many PCs the minimum brightness level allowed is not zero<sup>4</sup>, but a setting where ‘screen contents should be barely visible to the user’.

Finally, the profile contains a “negative brightness” curve, which represents the display response when further decreasing the brightness using a multiplicative factor applied to the gamma tables. In this way, brightness levels lower than the cut-off point can be achieved.

To map these brightness levels onto the correct behavior mimicking a reflective display, we used two manually-specified calibration points – at a high brightness and at the cut-off level. We found that just these two points allowed interpolation to the other brightness levels achievable by the backlight, and also accurate extrapolation to the negative brightness levels.

<sup>4</sup> e.g. <http://msdn.com/library/jj128356.aspx>

Calibration at the cut-off point was achieved by setting the display brightness to this level, and changing the ambient illumination so that the display (showing white) looks as bright as a white reflective reference (e.g. paper), and reading out the sensor value. Calibration at the high brightness point consisted of setting the lighting to maximum, and then adjusting the brightness of the display (showing white) so that it matched the reflective reference.

### 3.3 Realtime Ambient Illumination Matching

We now turn to the actual algorithm for matching the appearance of reflective surfaces. As shown in Fig. 2, the chromaticity and the brightness are processed independently.

**3.3.1 Chromaticity matching.** The chromaticity calibration points in the  $\hat{u}'\hat{v}'$  space are turned into triangles using Delaunay triangulation [25] as shown in Figure 5. The sensor's RGB values are transformed into the  $\hat{u}'\hat{v}'$  space using the primaries described above. The algorithm then finds the triangle that contains the sensed point. If no such triangle exists, it means the display is not capable of matching the chromaticity and the algorithm uses the closest point on any of the triangles as a best effort solution.

Once we have a point on a triangle, we determine its barycentric coordinates, i.e. its relative position in the triangle [26]. Each of the three  $\hat{u}'\hat{v}'$  calibration points of the triangle has a desired display output assigned (in  $u'v'$  coordinates). These desired colors form another triangle in the  $u'v'$  space. The algorithm's result is the  $u'v'$  point that is at the same relative position to the triangle in  $u'v'$  as is the sensed point in the  $\hat{u}'\hat{v}'$  triangle, effectively linearly interpolating the desired colors. Finally, the  $u'v'$  result is transformed using display primaries back to RGB for the display driver.

In total, the chromaticity matching part of the algorithm performs the following transformations:

$$\text{sensor RGB} \rightarrow \hat{u}'\hat{v}' \rightarrow u'v' \rightarrow \text{display RGB} \quad (1)$$

The final RGB values are used as linear coefficients in the graphic adapter's gamma lookup tables (LUT). LUTs are used by the graphics hardware as the last step of screen content composition, originally intended to compensate for non-linearities in CRT monitors. On Microsoft Windows operating systems, the SetDeviceGammaRamp function<sup>5</sup> can be used to load an arbitrary LUT in the hardware. Our algorithm modifies this to be a linear function of the result, e.g.

$$\text{output}_R = \text{display}_R \cdot \text{input}_R \quad (2)$$

This way, the chromaticity matching is applied globally to all content displayed on the screen without extra computational overhead.

**3.3.2 Brightness matching.** If the light level is between the two calibration measurements corresponding to the maximum brightness and the cut-off level, we simply linearly interpolate.

If the result requires brightness lower than the built-in backlight controller allows, the brightness calibration data is used to lookup the negative brightness value that would achieve the desired effect. The shape of the negative brightness curve is different for different displays and the algorithm linearly interpolates the value if needed.

**3.3.3 Negative brightness.** Realizing the negative brightness is the last step of our algorithm. It is achieved by uniformly decreasing the RGB result of the chromaticity matching. So, if desired brightness is negative, then the display is asked to output:

$$\begin{aligned} \text{output}_R &= \text{display}_R \cdot (1.0 + \text{desired brightness}) \cdot \text{input}_R \\ \text{brightness} &= 0 \end{aligned} \quad (3)$$

Therefore, as the ambient lighting decreases, the screen content eventually turns completely black.

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<sup>5</sup> <https://msdn.com/library/dd372194.aspx>

### 3.4 Mitigating Practical Issues

When testing our algorithm in real-world scenarios, a couple of issues were found that required specific mitigations.

**3.4.1 Angular response.** Typically, the sensitivity of RGB sensors varies significantly with the incident angle of the light (see the dashed line in Fig. 7 left). That means that the system is very sensitive to the relative position of the light source with respect to the sensor, and a system calibrated with straight-on light ends up too dim when the light is coming obliquely. In contrast, diffuse reflective surfaces such as paper have much more uniform angular responses, by scattering incoming light in all directions.

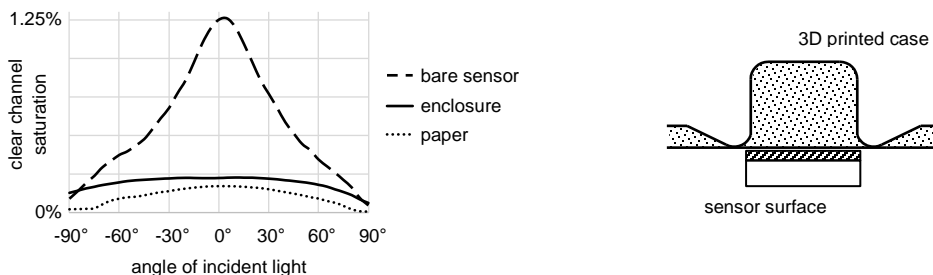


Fig. 7. RGB sensor's angular response (left) and cross section of a 3D printed case used to smooth this response (right). Dashed line – raw sensor performance. Solid line – 3D printed case performance (as shown on right). Dotted line – performance of paper diffuser for comparison.

In our prototype, we have mitigated the issue by covering the sensor using a 3D printed enclosure which attenuates the perpendicular light (depicted in Fig. 7 right and visible in Fig. 3 top left). After experimenting with various 3D printed shapes, we settled on a design which achieved a fairly flat response within  $\pm 60^\circ$  at the cost of overall sensor sensitivity (see Table 1 and the solid line in Fig. 7 left).

Table 1. The performance of our 3D printed case for angular response mitigation

angle	bare sensor attenuation	3D case attenuation
$\pm 30^\circ$	49%	2%
$\pm 45^\circ$	53%	9%
$\pm 60^\circ$	72%	20%
$0^\circ$	0%	80%

Optical components could provide a similar function without the loss of overall sensitivity, but they would add complexity and cost to the sensor hardware, and we found the loss to be acceptable during deployment.

**3.4.2 Flicker filtering.** Display flickering is very distracting and obviously counterproductive phenomena when trying to design a display that seamlessly blends into the environment. In initial trials, we identified two sources of flicker in our system – quantization flicker and sampling flicker.

Quantization flicker is caused by the light level being exactly at the boundary of two digital values reported by the sensor, resulting in a stream of alternating values. The lower the light conditions, the more visible this flicker is as it can result in dramatic differences in the algorithm results. This is mitigated using a simple averaging filter.

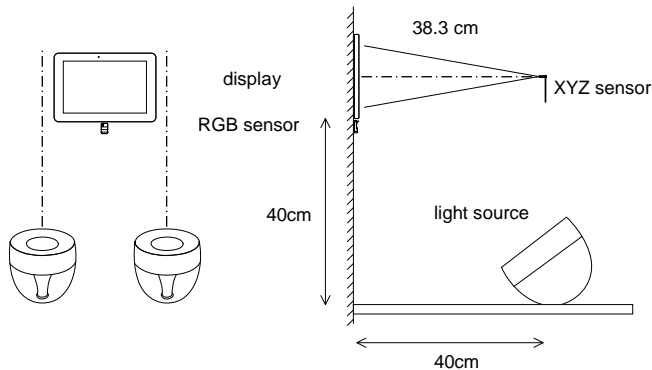


Fig. 8. Quantitative evaluation setup.

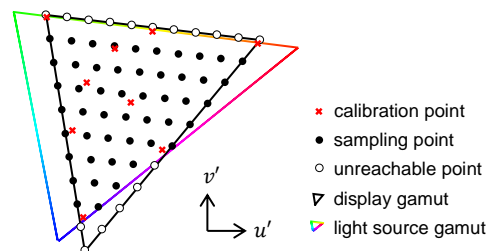


Fig. 9. Gamut sampling.

Sampling flicker is caused by the light source itself. Many light sources exhibit a high-frequency flicker and if the sensor readings are not synchronized with the light source flicker frequency, lower-frequency effects which are visible to the user can be introduced. To mitigate this, we introduced another smoothing filter, which blocks small changes in the output. Fig. 2 illustrates how these filters are incorporated into the algorithm.

**3.4.3 Backlight limits.** The biggest practical limits of the system are introduced by the built-in minimum visible backlight brightness. This is a feature protecting users from putting their devices into a state where they cannot control the UI of their devices because the backlight is off.

However, having the backlight on dimly causes even black screens to visibly glow in very dim and dark conditions. Since we are aiming at existing display devices, we have mitigated this issue by turning the display fully off once the desired display brightness drops below a minimum level (determined through preliminary testing in low-light conditions).

Note that this particular effect only occurs with LCD displays and would not occur with an OLED display.

## 4 COLORIMETRIC EVALUATION

We implemented the calm display algorithm using tablet PCs and our custom light sensor hardware, and evaluated it in a lab-based experiment to assess how well it achieves a colorimetric match with ambient lighting.

### 4.1 Experiment Design

The objective of the experiment was to measure the color differences between a blank sheet of paper and an emissive display running our algorithm and showing white color, across varying lighting conditions. We used a Fujitsu Q584 tablet with 10.1" 2560×1600 IPS screen, Xerox paper and Philips Hue lights as described in section 3.2.1, and Mazet's MTCS-C3 True Color sensor board for the colorimetry measurements. Compared to alternatives such as expensive spectrometers and spectrally tunable lights (such as [27]), the Hue lights and Mazet sensor are orders of magnitude cheaper and the Mazet sensor also integrates directly in the CIE XYZ space [24].

The setup is depicted in Fig. 8. A display with the RGB sensor is attached to a white wall made of foam core, lights are placed facing the display, and the XYZ sensor placed on the axis perpendicular to the center of the display so that the screen height constitutes 10° of the sensor's view. Since we are measuring differences only, the exact positions of the lights and distances are not important as long as they stay the same throughout the measurements.

Emissive sources are usually measured in the CIE LUV space [28], while reflective sources in the CIE LAB space [24] (both of which are easily computed from XYZ measurements). Since our aim is to make the display



look like a reflective medium, we chose to evaluate it in the LAB space. It bears noting though, that the conditions under which these spaces and metrics were designed differ considerably from ours (which includes varying lighting conditions from total darkness to very saturated colors), so the values are not directly comparable to other colorimetry measurements in the literature. Nevertheless, we believe our measurements provide a valid scale to evaluate our system.

The experiment was conducted as follows: The display and lights were turned on and to white for several minutes, so that they warmed up and the measurements were stable. A piece of paper was placed over the (inactive) display. The light was then set to produce several colors (described below) for 5 different brightness levels, and the color reflected from the paper was measured and recorded. Each measurement consisted of averaging 3 sensor readings each integrated over 400 ms. Then, the paper was removed from the display, the display was turned on (operating as described in Section 3), and the measurements were repeated for the same colors/brightnesses. Finally, the Euclidean distance error in the CIE LAB space  $\Delta E_{ab}^*$  was calculated for the display for each color/brightness combination, using the paper data as ground truth:

$$\Delta E_{ab}^* = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2} \quad (4)$$

As a white point reference, the display's white screen on full brightness was used. The Philips Hue lights are not able to match the full brightness range of the display in our setup ( $L^*$  ranges roughly from 20 to 63), and the color gamuts are also different as indicated by the triangles in Fig. 9. We sampled the display's gamut in  $u'v'$  uniformly using 66 points by dividing each side of the gamut triangle into 10 equally sized parts - see the points in Fig. 9 - and measured only those that we were able to match with our setup (50 in total). That way, the measurements could be directly compared to results achieved by other systems running on the same display. We repeated the above for five brightness level settings on the light source (2, 65, 128, 191, 254), corresponding to the  $L^*$  values of 20, 26, 38, 51 and 63 respectively, giving us a total of 250 measurement points.

## 4.2 Results

The average error across all 250 measured points was  $\overline{\Delta E_{ab}^*} = 6.16, \sigma^2 = 12.38$ , median 5.35. The distribution of the error can be seen on Fig. 11, including contribution from individual brightness levels. Fig. 10 further shows the individual color differences for three selected brightness levels ( $L^* = 20, 38, 63$ ). The color points represent the paper measurements and each of the point features a line to the corresponding display measurement.

To put the number into some perspective, under the metric's defined conditions, a value of 2.3 is usually considered as indistinguishable for two adjacent colors, although the threshold varies significantly across the space [29]. For example, one of the early but still often referenced works in this area uses the length of axes of the MacAdam ellipses [30] for the threshold, and this ranges from 0.9 to 9.9 with an average of 3.6 [31] in this color space. Color perception also considerably differs between individuals [32] and the threshold increases with complex content compared to a single patch of color [33]. ISO 15008 [34], concerning information presentation in transport scenarios (e.g. car dashboards), recommends that a distance of  $\Delta E^* \geq 20$  is used when portraying distinct colors.

To get a better idea of a threshold in comparable conditions to those in which our system is intended to be deployed (e.g. as in the bedroom scenario presented in the next section), we ran a small preliminary study, in which 6 participants had to adjust the display's colours and brightness using sliders, aiming to match the paper next to the display the best they could. This suggested an average threshold of  $\overline{\Delta E_{ab}^*} = 8.63$ .

In summary, our colorimetric evaluation shows that our system achieves an average error of  $\overline{\Delta E_{ab}^*} = 6.16$  compared to paper as ground truth. Majority of the measured points in all brightness levels except the darkest one had error of  $\overline{\Delta E_{ab}^*} < 5$  across the whole gamut. Based on existing metrics and our own analysis, a user of our system would likely be able to see a difference if given a reference image next to the display for comparison, however without such a reference image, the user is unlikely to notice the display behaving differently to paper. This gives us confidence that our system's performance in deployments is more than acceptable, and this was in agreement with the results of our field study described below.

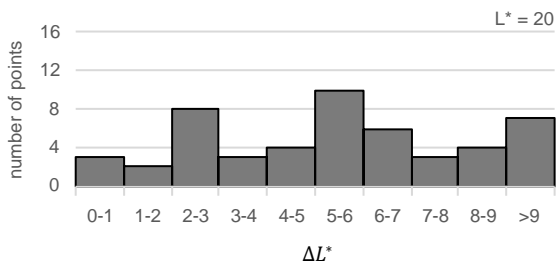
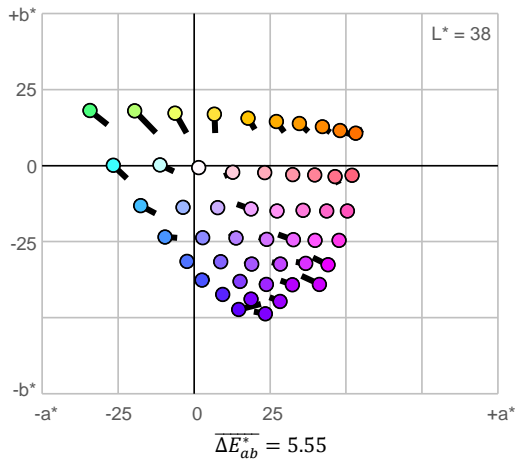
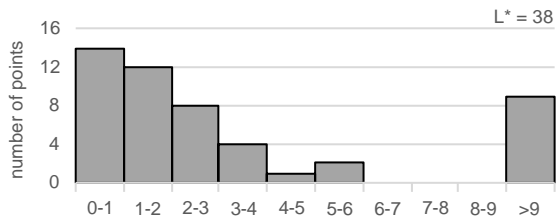
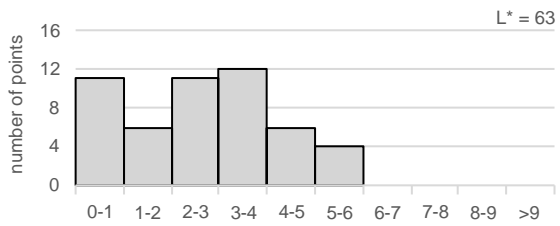
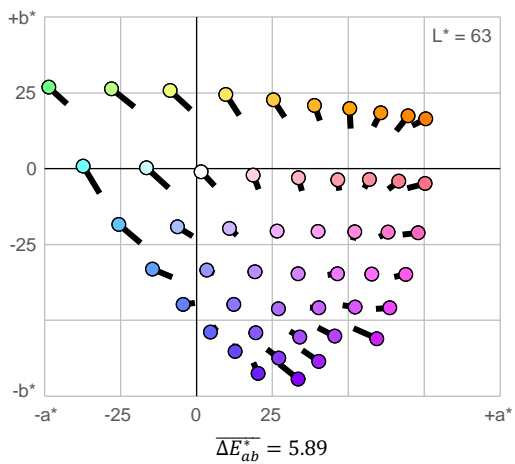


Fig. 10. For selected brightness levels, distribution of brightness differences (top) and individual chromaticity differences (left) between the display and paper.

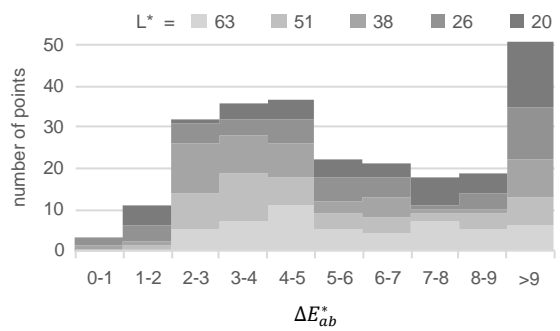
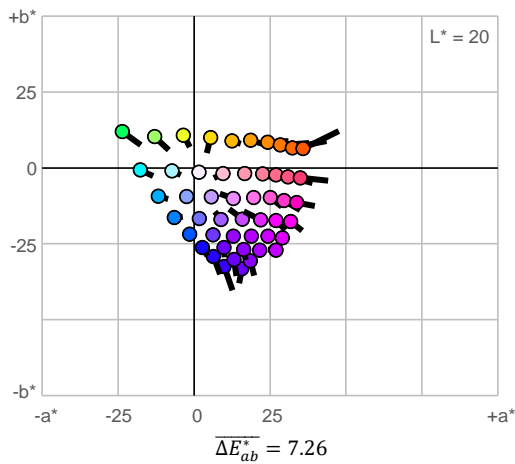


Fig. 11. Overall distribution of the measured color distances, shades reflect the brightness level.

## 5 BEDROOM STUDY

We deployed our calm display prototypes in a two-week field study in 12 participants' bedrooms, with three overall aims:

1. To validate our intuition that a “calm” display mode simulating a reflective display would be preferred over normal display behavior in the bedroom,
2. To verify that our specific implementation of the calibrated reflective-matching display algorithm and associated hardware had the “calm” qualities desired,
3. To gather feedback from users on their thoughts around calm displays having lived with one, in order to inform future work.

### 5.1 Study Design

Our overall study design is a within-subjects comparison of our “calm” light-matching display algorithm and a “normal” display. The normal display implements adaptive brightness as many tablet PCs do, but this is relatively unresponsive to the ambient light, as [Fig. 1](#) shows.

Participants received a 10.1” display tablet PC with attached RGB sensor and AC adaptor, and placed it in their bedroom in plain sight from their bed as shown in [Fig. 12](#).



[Fig. 12](#). An example of the deployed device in-situ.

The tablet showed a random slideshow of photos, advancing to the next image every 5 minutes with a 10-second cross-fading transition. The only interaction possible with the tablet was to toggle the display off or back on again using a hardware button. A label on the device highlighted the function of the button. If the participants turned the display off, it turned itself on again the following day at noon.

We split the study into two weeks, with half seeing the normal condition in the first week followed by the calm condition in the second week, and the reverse for the remaining participants. Participants were not informed of the differences between calm and normal conditions, nor that there would be two different weeks of conditions (until the second week).

The normal condition mimicked the measured behavior of an existing off-the-shelf device – switching between 24% brightness and 40% brightness level based on static ambient light intensity thresholds.

For privacy, the display was not connected to any network, all cameras and LED lights on the hardware were covered with opaque tape and disabled in the software. By replacing the Windows shell on the device with our study software, and by showing messages on the device if the mains power was ever unplugged or the sensor was unplugged, we ensured that the participants were not able to use the device for any other purpose, and that the device was operating properly.

We used two different types of tablet PC hardware, a high-end Fujitsu Q584 with 10.1" 2560×1600 IPS display and a low-end Linx 1010 with 10.1" 1200×800 IPS display. The types of tablets were balanced amongst the conditions. Participants were assigned their device randomly.

The twelve paid participants (aged 21-40 with median 32.5, 5 female) were recruited from a multi-disciplinary research lab in the UK, with the prerequisite of having only one bed in their bedroom. None of them were HCI researchers. 4 (2 female) had used electronic photo displays in the past.

This study design was approved using the ethics committee procedures for Newcastle University.

## 5.2 Data Gathered

During the study, we recorded various data: objective and subjective, qualitative and quantitative. Objectively, the device recorded the ambient lighting conditions and logged when the display was manually turned on or off, so we could see if people behaved differently with the calm mode or normal mode.

We gathered subjective data through a mid-study interview before the second condition was experienced and a final interview. In both interviews, the participants were asked to describe the operation of the device that week, allowing us to validate that the study procedure was followed. Questions concerning that week's condition were presented at both the mid-interview and final interview, while other questions concerning the value of the light-matching display mode and comparing the two conditions were only asked at final interview. The interviews were semi-structured, including both 1-5 Likert scale questions and freeform questions.

The specific interview questions asked will be presented in-line with the results in the next section.

## 5.3 Results

For two of the participants, the mode of their device was not set correctly for both weeks: one (#11) was meant to have calm mode in the initial week but had calm mode both weeks, while another (#12) was meant to have normal mode in the initial week but had calm mode both weeks. The remaining ten participants (#01 to #10) who saw both conditions were correctly balanced (5 seeing the calm mode in the first week). Since #11 and #12 saw the calm mode, we retained their freeform responses concerning the value of this mode, but excluded all their responses and data for analyses comparing the calm and active mode.

Participants #01-10 all responded to the mid- and final-week interview question about describing the behavior of the system during each week, reporting no significant issues with the operation of the device (e.g. no device was powered down at any point). The software log files also confirm the device was operating correctly. This gives us confidence in the resulting data.

We also asked participants which nights the bedroom was unoccupied, and excluded six nights from the results as a result. One participant started the study one day late.

**5.3.1 Observed behavior.** Logs from the devices confirmed that on 59 nights out of 68 (87%), participants turned the normal display off overnight. In contrast, there was only single night out of 63 (2%) on which the calm display was manually turned off (see Fig. 13 for per-participant data). This observed behaviour in a real-world deployment is very encouraging for the potential for calm displays in ubiquitous computing scenarios.

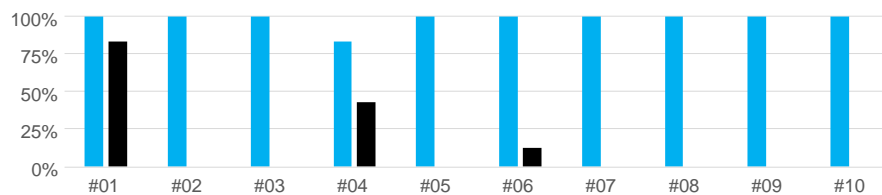


Fig. 13. Percent of the nights on which individual participants kept the display on (blue=calm, black=normal condition).

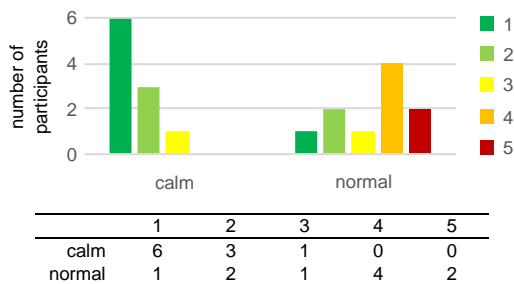


Fig. 14. Was the display distracting? (1=not distracting, 5=very distracting).

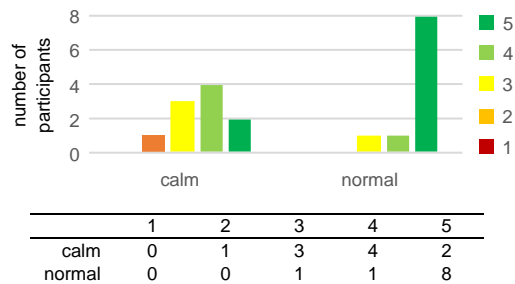


Fig. 15. Were you able to see the content when you glanced at it? (1=very difficult to see, 5=very easy to see).

5.3.2 *Distraction*. We asked participants how distracting they found the display on a scale from 1 (not distracting) to 5 (very distracting). 6 out of 10 participants marked the normal display as distracting (i.e. scoring it 4 or 5), while none marked the calm display as distracting, see Fig. 14. Fisher’s 2×3 exact test [35] shows a statistically significant difference in the perceived distraction ( $p = 0.005$ ).

During the interviews, six participants described the normal display as “too bright”, in spite of the fact that it was never above 40% of its maximum brightness. Five participants explicitly commented on the non-distracting nature of the calm setting. Participants noted that the display was “unobtrusive” (#07) and “blends in with the rest of the room” (#01).

5.3.3 *Visibility of content*. Since the calm display aggressively controls the brightness and chromaticity through gamma settings, we were interested whether that has any significant effect on the ability for participants to see the content on the display.

We asked the participants whether they were able to see the content when they glanced at the display, ranking from 1 (very difficult to see the content) to 5 (very easy to see the content). The results are shown in Fig. 15. Fisher’s exact test doesn’t show a statistically significant difference in content visibility ( $p = 0.303$ ).

It was expected that the content on a normal display would be perceived as easier to see and indeed, within-subject comparison confirmed this expectation, as shown in Fig. 16.

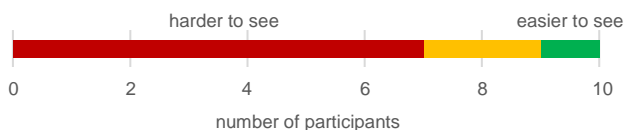


Fig. 16. Within-subjects content visibility scoring of calm display compared to normal display.

Half of the participants stated to various degrees that the image on the calm display was perhaps too dim, but all of these participants had the lower-end tablet, which has a worse viewing angle.

*Content during the day is quite easy to see, but during the evening it was a bit more difficult. #04*

We also used a more objective way of assessing whether participants could see the content, through a memory recall test. The photos shown on the display were 10 pictures of flowers and fruits for the first week and 10 pictures of landscapes and trees for the second week, downloaded from public collection of wallpapers<sup>6</sup> (see Fig. 17 for examples).

<sup>6</sup> <https://support.microsoft.com/help/13768>

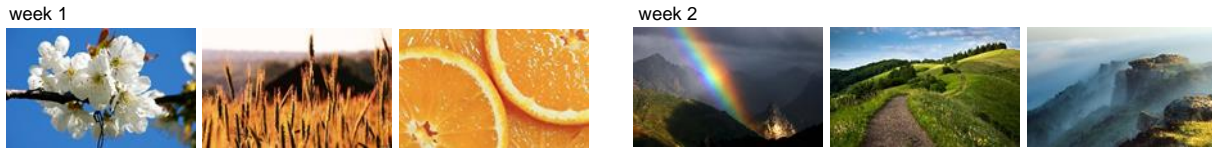


Fig. 17. Examples of images used during the study.

After the first week, we presented the participants during the interview with a sheet containing 30 photos of fruits and flowers (10 of which were shown on their display during that week) and asked them to mark the ones they recalled seeing. We performed a similar test after the second week, presenting a set of 30 pictures of landscapes and trees, of which the display had been showing 10.

The results are summarized in Table 2. We found no significant difference in the recollection performance between the normal display and calm display conditions.

Table 2. Average number of pictures recalled.

	correctly	incorrectly
calm display	3.4	1.0
normal display	3.2	1.2

5.3.4 *Matching fidelity.* Although we didn't inform the participants that our algorithm was designed to mimic a reflective surface, two participants compared it to a printed picture and one to the walls.

*The screen was the same brightness as the walls, which was pretty impressive, I didn't know you can make the screen that dim. #10*

*It's a nice ambient thing, like a regular picture in a way – you don't notice that it's there unless you are looking for it. #02*

5.3.5 *The bedroom environment.* The light levels of a typical day in a bedroom are shown in Fig. 18. Note that on the left image, the amount of light coming from the indoor lighting is larger than the amount of light coming from outside, but it is vice versa for the participant on the right. The sudden appearance of daylight is most likely caused by opening curtains in the evening. All participants but one reported during the initial interview that they sleep with curtains closed.

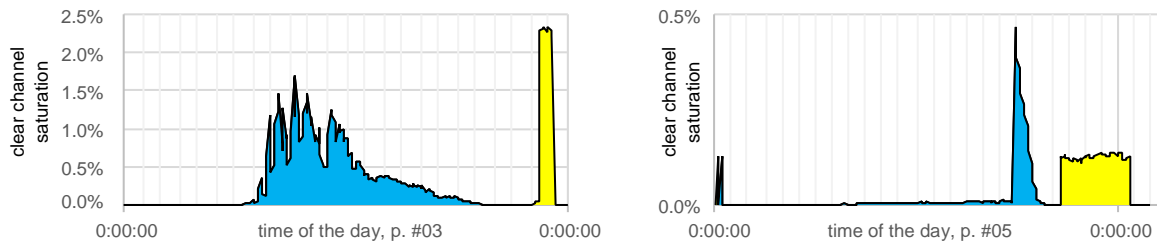


Fig. 18. The light level during a typical 24-hour period in two different participant bedrooms; blue shows daylight and yellow indoor lighting. The vertical axis is absolute sensor saturation, note that the left scale is 5x the right scale.

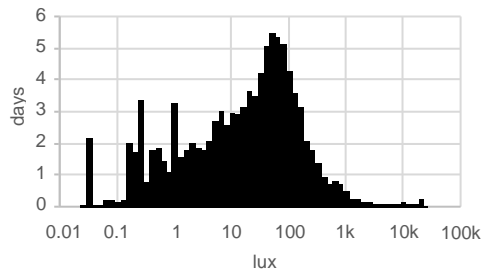


Fig. 19. Distribution of illuminance values measured.

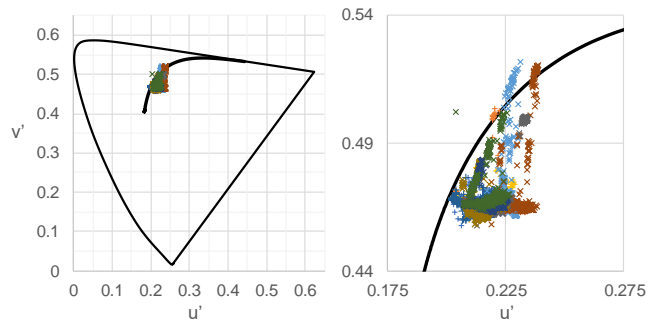


Fig. 20. Applied chromaticity results.

The overall distribution of illuminance values measured during the study is shown in Fig. 19. The sensor read zero illuminance for 86% of the time (not shown in the figure). These values indicate that the environment is often very dark. During the calm condition, the high-end tablet used negative brightness for 65% of the time, the low-end tablet for 50% of the time, which implies it is an important feature of the system.

*[The light level] is the key thing if you want to put [a display] in your bedroom. #05*

As for the chromaticity, none of the participants had any colored lighting in their bedrooms. All the algorithm results applied during the study are plotted in Fig. 20 (each participant shown in different color). The black line is the Planckian locus, denoting the chromaticity of a black body as its temperature changes from 1000K to 40,000K.

One participant noticed and highlighted the importance of chromaticity adjustments.

*It's very good at adjusting between the white light that comes out of the ceiling light and the creamy orangey light from the bedside light. #12*

Another participant mentioned that the white balance seemed wrong (see Fig. 21). This issue is due to our sensor's sensitivity, mostly of the red channel, to the infrared light, and its inability to distinguish between infrared and visible light. Infrared light is particularly present under incandescent light and sunlight.

The solution to this problem is either to use a sensor that is not sensitive to the infrared light, or to add an infrared filter.



Fig. 21. Suboptimal colors caused by infrared light.

**5.3.6 Appropriateness for Bedrooms.** We asked whether the participants thought that the light-matching display mode was more appropriate for use in bedrooms, from 1 (much less appropriate) to 5 (much more appropriate). 8 out of 10 participants said it is more or much more appropriate, see Fig. 22. Note that we did not mention “calm” to participants.

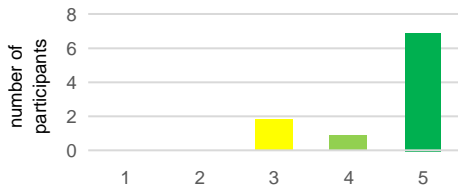


Fig. 22. Are calm displays more appropriate for bedroom use? (1=much less appropriate, 5=much more appropriate).

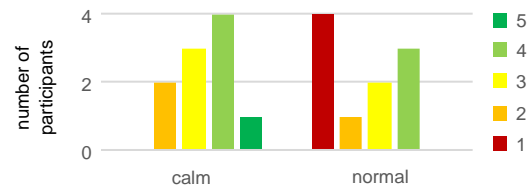


Fig. 23. Would you want a display like this in your bedroom long-term? (1=definitely not, 5=definitely yes).

We asked participants whether they would like to have a display like the one used during the study in their bedroom long-term, from 1 (definitely not) to 5 (definitely yes), provided they could customize its appearance to their liking and that the display was affordable. The distribution of answers can be seen in Fig. 23, and the within-subject comparison in Fig. 24. Fisher’s exact test doesn’t show a statistically significant difference in the preference of having such display in a bedroom ( $p = 0.523$ ).

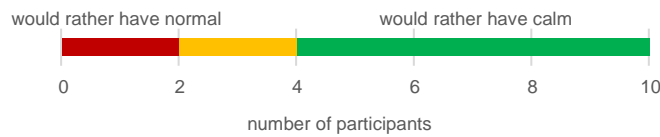


Fig. 24. Within-subjects’ scoring on the desirability of having calm vs normal display in their bedroom.

5.3.7 Types of content shown. All but one participant said that personal photos would definitely be their choice of content, and 9 participants ranked photos as the most important of the content they were considering. This is perhaps not surprising given the resemblance of our prototype to a digital picture frame.

*When I was younger I never really saw the value in photographs. Now with the family and with more to look back on, it’s nice to see something that triggers a positive memory, even if just fleeting. Nice to wake up to, or to see just before you go to sleep. To start the day in a positive way or to finish on a high note at the end of the day. #02*

Two participants preferred different content over photos – a to-do list, a calendar (#03), appointments and weather (#01). The complete list of content suggestions is summarized in Table 3.

Table 3. Display content suggested by 12 participants.

participants	content
11	photos
4	weather
3	calendar/appointments/schedule
2	social (FB, Twitter, Instagram)
each once	to-do list, time, BBC news, audio control, quotes & tips



Table 3 reflects uses that participants came up with themselves. We additionally asked participants who only specified photos whether weather and time would be useful. Only participant acknowledged time as useful; another dismissed it as something that they are using their phone for. 4 participants acknowledged that weather would be useful.

5.3.8 *Other environments for calm displays.* When asked if they can think of any other environment where our system would make displays more appropriate. 7 participants said that our algorithm can and should be used on displays anywhere in the home, whereas 4 participants suggested just the living room.

*I'd probably use it anywhere. I think it is nice to just have something that adjusts to [the light] – I'd have something like that in my lounge, because I have different types of lighting within my lounge, I don't think it's just bedroom only. Personally I think it could work anywhere. #12*

The television use case was a popular example among living room suggestions.

*If you were watching TV at light night, if you were watching film, you wouldn't necessarily want really brightly lit photo display on at the same time. #01*

*If I was in the living room, watching something on the television and I dimmed the lights, it would be useful if it dimmed as well. #03*

## 6 DISCUSSION AND FUTURE WORK

### 6.1 Building Calm Devices

The results of our evaluation suggest that displays that are responsive to ambient lighting are less distracting and more environmentally appropriate. These results are encouraging for researchers and designers of ambient information systems since it implies that devices with high-resolution emissive LCD displays, which are in widespread use, can be used in "calm" applications. This is an interesting development since designers have previously argued against the use of these displays due to their attention-grabbing nature [36].

However, our findings also suggest that matching ambient illumination alone may not be enough for creating a calm device. Ambient illumination matching only provides a way for information to fade into the periphery. However, calm technologies also need to provide a way for information to easily return to the center of attention. An example of this problem manifesting itself was when one of our participants commented that the "calm" display condition had decreased visibility, which they found distracting. Consequently, we believe that future work in calm devices will need to investigate lightweight mechanisms to bring information back into focus.

### 6.2 Future Display Technologies

Our data show that during the study, at least 86% of time the device could be turned off completely and save power without any impact on user's experience, because it is dark, while automatically coming back on when it is light again, enabling the user to glance at the display at will. Using our system with OLED displays would result further power savings when active, as OLEDs consume power in proportion to the brightness they emit. Since the performance of our system depends only on the capabilities of the display such as its dynamic range and color gamut, we believe that our system would perform even better with OLED displays, without any further modification.

One of the limitations of the presented system is that it depends on the display using 3 primaries (typically red, green and blue). The color gamut of displays can also be extended with additional primaries, such as yellow and cyan. Cheng et al. [37] has prototyped such LCD, and Sharp is currently offering a commercial display with

an extra yellow primary<sup>7</sup>. Furthermore, future displays based on quantum dots technology can offer arbitrary primaries. For these applications, the algorithm would have to be redesigned to fully take advantage of the displays extended gamut range.

## 7 CONCLUSION

In this paper, we report on a new approach to creating calm ambient displays which we have designed, implemented and deployed. In our system, we control a display's backlight intensity and gamma correction to match the ambient lighting conditions. We believe our approach is both robust and practical; in particular, it does not require a per-device calibration step, runs in real-time and the only additional hardware required is a commodity RGB light sensor. We therefore believe the technique could be used at scale.

Having described our implementation and the theory behind it in some detail, we presented the results of a field study we ran, deploying prototypes in users' bedrooms for two weeks, providing direct comparison of our system and the status quo in current display technology (adaptive brightness). We presented both quantitative and qualitative results from the field study; both of these indicate that our new approach is less obtrusive than a regular display would be, and yet provides nearly as much utility. Eight out of the ten participants said that our system makes the display more appropriate for use in bedrooms compared to existing displays, while the others were neutral. We provide direct rather than conjectural evidence about the distracting and inappropriate nature of current display technology for ubiquitous deployment and want to explicitly point out to non-existent efforts in the community to address these hardly surprising results.

The over-arching aim of our work is to create new opportunities for the use of ambient displays in the environment. We envisage a future where a variety of emerging emissive display technologies such as flexible LCDs and OLEDs become widespread. We believe that supporting a "calm" mode of operation which allows these displays to fade into the background will be a pre-requisite for adoption. We hope that others will be able to build on our work and ultimately move us closer to a world of calm technology.

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