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B. Wang and A. Wilkie (Guest Editors)

Temporal Brightness Management for Immersive Content Supplementary material

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1. Further details on the brightness management

Calibration Figure 1 shows the impact on brightness modulation when varying the value of ΔL, the maximum tolerable luminance change, within a fragment of the Village sequence. The Viking Village is set by the sea in the evening, under a partially cloudy sky. It contains several wooden houses and handmade objects, as well as grassy areas and bright, flaming torches. As for the other scenes, we use a camera path that traverses illuminated areas and dark spots, moves closer to the torches, and reveals views of the sky and sea.

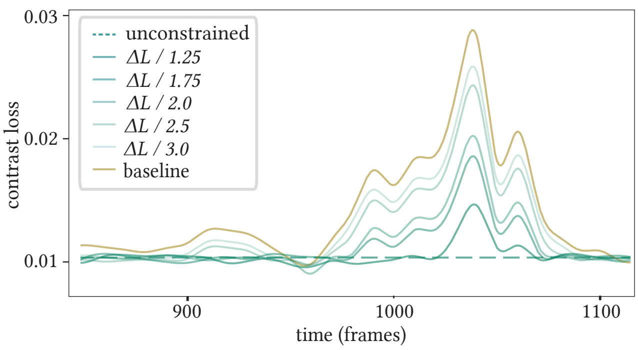

Figure 1: *This figure illustrates the effect of applying different constraints on luminance changes within a fragment of the* VILLAGE *sequence. Under unconstrained optimization, the method maintains a constant visible contrast loss (dashed line) across the sequence. However, as the tolerable luminance change decreases, the modulation becomes more restricted, eventually approaching constant brightness. Consequently, the corresponding contrast loss gradually converges to that of the baseline (yellow), where the modulation applies uniform dimming.*

Modulations We report in Figure 2 additional modulation curves for the scene LIVING ROOM at different average power consumption targets.

In addition, for a direct comparison with the real-time version of our method, we ran the PID-based control scheme targeting a contrast loss of 0.25, which results in an average brightness factor $\bar{b} = 0.43$. This result is compared with the offline approach

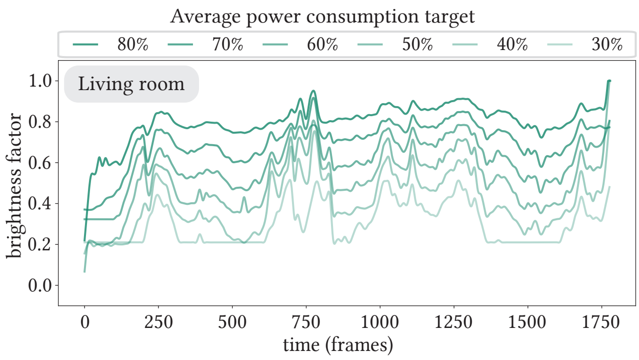

Figure 2: *This figure shows the results of the optimization when targeting different average power consumption on the sequence* LIVING ROOM. *The modulations exhibit similar trends due to the content-dependency.*

achieving the same $\bar{b}$. Figure 3 shows the related plots of brightness and contrast loss for both the real-time and offline versions. While the offline approach is able to achieve a target power budget, the real-time aims to save power by maintaining a consistent contrast loss. Despite lacking information on future frames, the real-time approach still exhibits similar trends as the offline method.

2. Further details on hardware

VR headset For all our perceptual experiments, we used a Varjo XR-3 headset equipped with a double display: the focus area is 70 PPD uOLED, 1920 x 1920 px per eye, while the peripheral area is 30 PPD LCD resolution of 2880 x 2720 px per eye. The refresh rate is 90 Hz. The peak luminance we measured is 103 $\frac{cd}{m^2}$, while the black level is 0.2 $\frac{cd}{m^2}$. Display gamma is measured at 1.95.

LCD Panel The panel the Raspberry Pi 7" standard LCD panel, a RGB display with a native resolution of 800x480 and a peak luminance $L_{max} = 750 \frac{cd}{m^2}$. The backlight is LED and controllable via software through the Rapsberry Pi.

We assume that the backlight of the LCD panel is always set to its maximum. Therefore, our modulation effectively scales the

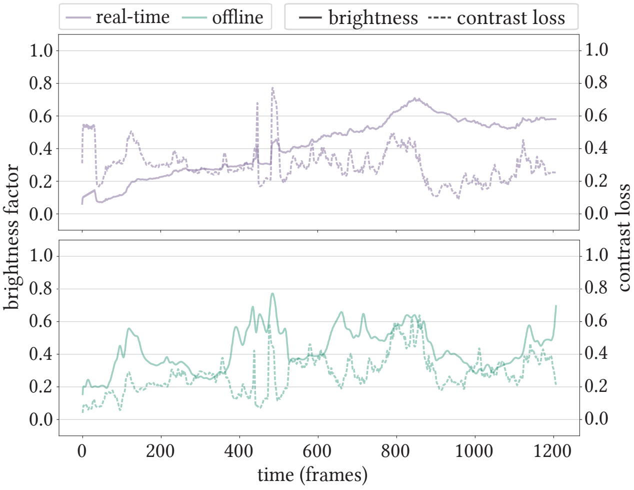

Figure 3: *A comparison between the offline optimized brightness and the real-time brightness computed using the PID controller for the* LIVING ROOM *sequence. The two brightness curves have the same average brightness factor 0.43. The offline method has an average contrast loss* $\bar{\mathcal{L}}_c = 0.279 \pm 0.116$*, while for the real-time we measured* $\bar{\mathcal{L}}_c = 0.298 \pm 0.132$.

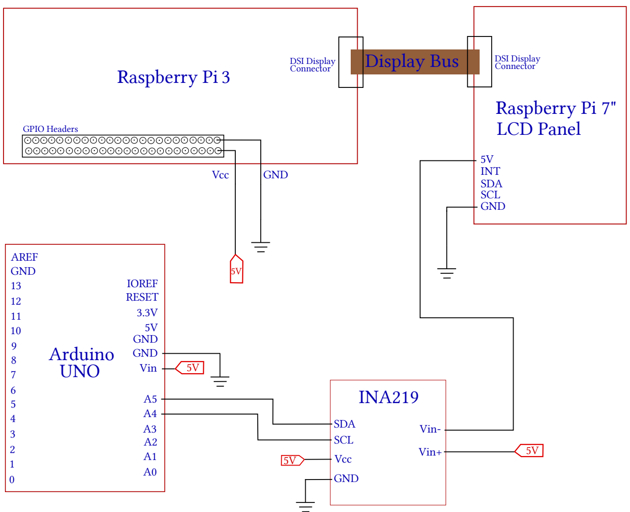

Figure 4: *Schematic of our VR setup mockup. We use an adjustable voltage power supply (Basetech BT-155), which externally powers a Raspberry Pi LCD display (see Supplemental for a complete spec). An external Arduino Uno is used to continually measure the power consumption of the LCD monitor throughout the experiments, using an INA219 current sensor.*

peak luminance of the screen, resulting in the luminance of each frame being $L_i = L_{max} b_i$, thereby removing the dependency on the frame content I_i. Certain types of displays might employ different strategies, such as scaling the peak-luminance of the frame as $L_i = \max(I_i) \cdot b_i$, or using more complex local dimming techniques, as seen in OLED displays.

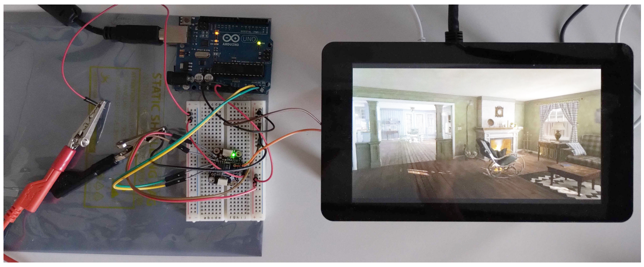

Figure 5: *A picture of our built-in circuit. On the left, the red and black cables supply power to the circuit with the desired voltage and current, adjustable via the Basetech BT-155. On the right is the 7" LCD Panel, displaying a frame from the* LIVING ROOM *sequence. The Raspberry Pi is connected to the panel and positioned behind it, making it not visible. The sensor on the breadboard measures the intensity of current, which is recorded by the Arduino, located in the top left of the picture.*

3. Further details on Performance Experiment

Study The full experiment contained four series, each series containing four trials. Each trial involved finding the unique Landolt ring visible at a specific location. Subjects could look around the area to find them; however, modulation is not re-computed during the interaction. We assume the impact of luminance accommodation to be small given the broad uniformity in illumination within the selected areas and that contrast sensitivity is local, implying that the Landolt rings will be perceived similarly regardless of camera orientation. We annotate the timestamps of the selected locations with vertical colored lines and show corresponding frames in Figure 7 of the main paper.

Stimuli Landolt rings were positioned at different locations within the field of view, with random orientations, such as on walls, labels, the floor, and objects (Figure 6), but never behind the participant. They were integrated into the scene by overlaying them on the background texture and rendering them with varying hue, saturation, and alpha values to closely match the background texture while also varying their visibility. It is important to note that our method analyzes only luminance and does not account for color.

Study 20 people naive to the study with normal or corrected-to-normal vision participated in the experiment (ages 23-31). They were divided into two groups: one group was exposed to the locations of the two sequences LIBRARY and LIVING ROOM with our brightness modulation (denoted as OURS), and the other two sequences, GYM and BASEMENT, with the BASELINE. The second group experienced the sequences with the methods reversed.

For each location, the participants could rotate the camera/head in any direction to spot the ring. We assume small head movements have minimal impact on letter visibility, as the content is uniform and brightness remains constant during movement. The task of the participants was to spot the orientation of the gap on the Landolt ring, by pressing the corresponding arrow key. After the ring was found, the participant was teleported to the next location.

Figure 6: *Samples of the Landolt rings displayed during our performance experiment. The last two on the right have been exposure corrected for better visualization.*

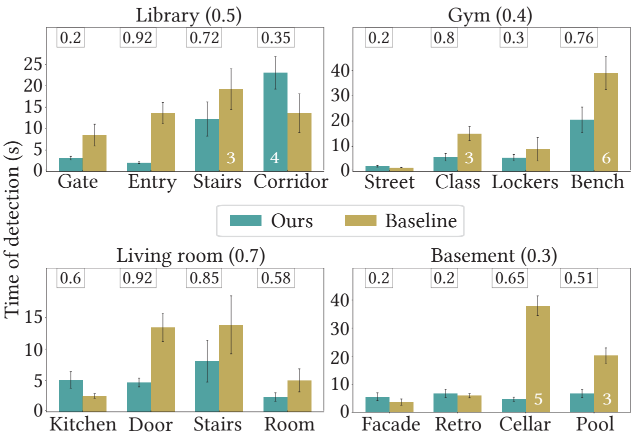

Figure 7: *For each location in the four sequences, we report the average detection time. The white numbers indicate trials where the ring was undetected, and the number above each column shows the modulated brightness used. The baseline brightness, in brackets, is constant across all locations in each sequence.*

Results Figure 7 presents the average detection times for each location, along with the standard error of the mean. We filtered the data by pruning detection times over 60 seconds, which meant the sample went undetected, since their inclusion would skew our analysis drastically. Furthermore, variability in the results may be attributed to external factors like attentional shifts towards irrelevant areas of the image, particularly in more complex locations with numerous stimuli.

We can observe that detection times were significantly reduced in low-brightness environments (since our modulation boosts it to prevent further loss of contrast). Furthermore, in bright areas, our modulation did not significantly impact detection time, while saving energy vs the baseline via reduced brightness. In rare cases (e.g. *Corridor*), however, our method reduces brightness too aggressively to maintain effective contrast. Although our algorithm achieves consistent contrast losses, it operates globally, which may lead to specific features being compromised, such as the Landolt in this case.

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