RadialLight: Exploring Radial Peripheral LEDs for Directional Cues in Head-Mounted Displays

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ABSTRACT

Current head-mounted displays (HMDs) for Virtual Reality (VR) and Augmented Reality (AR) have a limited field-of-view (FOV). This limited FOV further decreases the already restricted human visual range and amplifies the problem of objects going out of view. Therefore, we explore the utility of augmenting HMDs with *RadialLight*, a peripheral light display implemented as 18 radially positioned LEDs around each eye to cue direction towards out-of-view objects. We first investigated direction estimation accuracy of multi-colored cues presented on one versus two eyes. We then evaluated direction estimation accuracy and search time performance for locating out-of-view objects in two representative 360° video VR scenarios. Key findings show that participants could not distinguish between LED cues presented to one or both eyes simultaneously, participants estimated LED cue direction within a maximum 11.8° average deviation, and out-of-view objects in less distracting scenarios were selected faster. Furthermore, we provide implications for building peripheral HMDs.

ACM Classification Keywords

H.5.1. Information interfaces and presentation (e.g. HCI): Multimedia information systems: Artificial, augmented, and virtual realities.

Author Keywords

Head-mounted displays; Augmented reality; virtual reality; directional cues; wide field-of-view; peripheral display; LEDs

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(a) Frontal view. (b) Zoom in view. (c) Study participant.

Figure 1: *RadialLight* prototype. *Best seen in color.*

INTRODUCTION

Current Augmented and Virtual Reality (AR, VR) devices suffer from a limited field-of-view (FOV). While the human visual system has a FOV exceeding 180° horizontally, current head-mounted VR devices (Oculus Rift[1]) are limited to around 90° horizontally, and AR devices (Microsoft Hololens[2]) to around a 40° horizontal view. This means that in the user's periphery, either parts of the visual scene are missing in VR or no virtual content is visible in AR. This is partly due to technical limitations, where extending the FOV of such devices requires more pixels to calculate, emits higher heat radiation, and results in lower wearing comfort due to increased weight. Importantly, this restricted FOV limits the immersive potential of these systems. Especially for VR scenarios, which often rely on user awareness of the position of out-of-view objects that lie outside of this restricted FOV (e.g., opponents in a multi-player game). This leaves visual information-processing capabilities of users underutilized. Furthermore, the experience of users is less immersive because of an abruptly ending display.

To support directional cueing of out-of-view objects in VR and AR space, we build on prior work (cf., Xiao and Benko's SparseLight [12]) and propose *RadialLight*, a radial peripheral light display (Fig. 1). Compared to SparseLight, *RadialLight* consists of equally distributed radial LEDs making full use of the 360° space available. *RadialLight* is implemented as

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[1] `https://www.oculus.com/rift`, May 28, 2018
[2] `https://www.microsoft.com/en-us/hololens`, May 28, 2018

a proof-of-concept prototype to aid directional cueing (with relative direction mapping to select objects). This helps avoid rendering the full environment, and can aid in drawing attention to particular objects in the user's periphery. Moreover, since this display can be lightweight and inexpensive to construct, it can easily be modified to augment existing HMDs. Furthermore, showing the direction of out-of-view objects is one common example of how one could use radial light displays. In *RadialLight*, we ensured that each LED can be perceived with the same accuracy irrespective of position. This is especially important in critical situations, e.g., pointing in the direction of approaching danger.

In this paper, we explore how accurately can participants perceive radial peripheral light displays that make use of different colors to visualize directional information (e.g., the direction of an out-of-view object). Furthermore, we investigate the effect that different background scenarios have on direction estimation where we introduce a search task to test ecological validity of our results. In our experiments, we show that participants could not distinguish between LED cues presented to one or both eyes simultaneously, participants estimated LED cue direction within a maximum of 11.8° average deviation, and out-of-view objects in less distracting scenarios (ship bridge) were selected faster but with similar directional accuracy. Our findings support prior work [12] that peripheral displays can be useful in expanding the FOV in HMDs. We make two contributions to mobile human-computer interaction: (1) An empirical evaluation that shows the effectiveness (in terms of cue directional accuracy and out-of-view object search time) of our system in 360° VR scenarios. (2) We introduce RadialLight, a low cost radial peripheral display that augments existing HMDs, implemented as 18 radially positioned LEDs around each eye to cue direction.

RELATED WORK

Direction Cueing in HMDs

Lin et al. [6] investigated guiding gaze in 360° videos on smartphones. They presented two approaches for guiding attention in 360° videos: Auto Pilot (bringing target to viewers) and Visual Guidance (indicating direction of target). They showed that if increased head movement is necessary (e.g., following a sports video), users preferred Auto Pilot. Furthermore, users found it frustrating to shift to a target that is already gone. This highlights the need for directional cueing. Gruenefeld et al. [1] adapted existing off-screen visualization techniques to head-mounted AR, where they mapped out-of-view objects onto a sphere to aid direction cueing using adapted Halo, Wedge, Arrow. They showed Wedge and Halo outperform Arrow, however these techniques perform worse with increasing angles towards out-of-view objects. Therefore, EyeSee360 was developed [2] to cue direction with an accuracy independent of the angles towards the visualized out-of-view objects. However, the radar-like presentation in EyeSee360 increased the workload of the participants significantly.

Peripheral Displays and Wide FOV HMDs

Orlosky et al. [9] present a method to extend the limited FOV of HMDs by a fisheye view that compresses the peripheral aspect. They found that users are able to detect 62.2% of objects distributed in 180° while they can detect 89.7% with the naked eye. This however works for environments in 180° on a smaller FOV, and has a negative effect on perception of detected objects since smaller objects can disappear because of the compression. Yamada and Manabe [13] presented a method that uses two different lenses with different magnification. While their prototype was usable for extending the FOV, two levels of magnification means the foveal FOV is clear while the periphery is milky, and this lack of detail is not suitable for visualizing out-of-view objects. Nakuo and Kunze [8] present an initial peripheral vision glasses prototype, that can display patterns in the peripheral vision of the user. However, their prototype is limited in what can be shown in the left and right periphery and does not include different object positions, making it unsuitable for directional cueing.

Xiao et al. [12] presented SparseLight, introducing a matrix of LEDs placed in head-mounted VR and AR devices to create higher immersive experiences. They showed SparseLight's usefulness in conveying peripheral information and improving situational awareness, and reducing motion sickness. While we use direction cues to indicate position of out-of-view objects, they use visual clones shown on multiple LEDs in an absolute mapping. This makes our approach more suitable for representing direction cues irrespective of how far in the 180° far periphery view. Moreover, we encode out-of-view objects with a single LED on a radial LED ring instead of using multiple changing LEDs with varying distances to the eye, which ensures objects can be perceived with equal accuracy and with lower processing cost.

RADIALLIGHT SYSTEM

RadialLight (Figure 1) was built using the prototyping tool PeriMR [3]. It is based on prior work from Xiao et al. [12] and uses the Google Cardboard platform, which combines a smartphone with cut cardboard to create a VR and video see-through AR device. We modified Google Cardboard to include laser-cut plexi-glass as diffusor, and to ensure a more solid foundation. We added 18 radially positioned and individually addressable RGB LEDs (WS2812B) around each eye to cue direction towards out-of-view objects. To control LEDs, we used a NodeMCU developer board[3] (ESP8266) with a low-cost Wi-Fi board attached, that serves as a Wi-Fi access point. The board is powered by a Li-Po battery (3.7V). We developed a REST-API to directly change LEDs over Wi-Fi from a Google Pixel XL smartphone via Web Requests. As such, *RadialLight* is a standalone headset that does not require connection to any external device.

RadialLight's FOV with LEDs around each eye is shown in Figure 3. The human monocular FOV [10] showing foveal, near and far peripheral vision for each eye is shown in yellow, blue, and gray, respectively. Given related work [4, 11], we used colors that are perceivable outside the smartphone's FOV: yellow, blue and white. We adapted our LED placement to fit the nearest perceivable color, i.e. yellow. For our experiment, we used these colors (blue, yellow, white), which map to one, two, or all RGB channels, respectively. To ensure optimal

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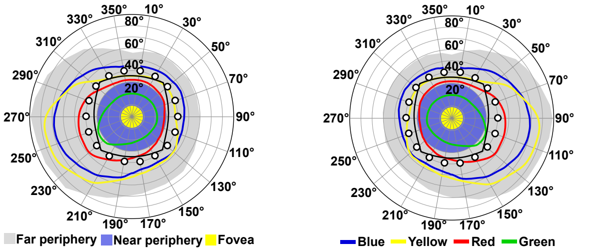
[3] `https://en.wikipedia.org/wiki/NodeMCU`, May 28, 2018



(a) Left eye.

(b) Right eye.

Figure 2: *RadialLight's* LED placement relative to human FOV. Black line: *RadialLight's* smartphone FOV. Color lines: human color perception. Circles: LEDs. *Best seen in color.*

viewing, we placed LEDs in radial formation around the user's eye to ensure every LED will be perceived with similar perceptual characteristics given the decreasing level of detail a human eye perceives with increasing radial distance [11].

To guide head movement using direction cues, we followed Gruenefeld et al.'s approach [1], where a virtual sphere around the user's head is used to map all out-of-view objects onto. Each point on this sphere indicates direction towards an out-of-view object. If we consider the user's line of sight as also a point on that sphere, an imaginary line on the surface of the sphere between these two points indicates the head movement necessary to see the object. Here, head-movements are limited to 90° in vertical and 180° in horizontal plane. Therefore, we restricted the FOV to 180° in front of the user, wherein each shortest path on the sphere becomes the optimal head movement towards the object. An advantage of our approach is that it easily extends to 360° around the user, since cues are independent of head movements. Practically, this means there are no difference between 90°, 145°, or even 180°. However, since we cue direction towards out-of-view objects we suggest to cue only one object at a time. Otherwise, most of the time many LEDs would be lit (at least those near the horizon, since even virtual environments tend to place objects along a ground plane) and it will be unclear to the user where to look.

STUDY I: DIRECTIONAL ACCURACY AND LED COLOR

We first investigate directional accuracy across colors in *RadialLight* to find the average direction deviation error across LED positions. We tested LED color differences using either a background (white) or no background (black space). Second, we investigated user performance when cues were presented to one versus both eyes.

Study design

To evaluate directional accuracy across LED colors, we ran a lab-based user study in an empty white-walled room with darkened windows (to avoid effects of different light conditions). Furthermore, *RadialLight* was designed to minimize incoming light (by placing material around the frames).

(a) Arrow manipulated with jog dial. (b) Out-of-view object on right side.

Figure 3: (a) Direction estimation task with background condition. (b) Out-of-view object search task with car cockpit condition. *Best seen in color.*

Our experiment consisted of a 3 (Color: blue vs. yellow vs. white) x 2 (Background: no background vs. white light) repeated measures design, where we measured cue directional accuracy (our dependent variable) as well as subjective Likert-scale measurements. Furthermore, we tested differences between switching on LEDs to both eyes versus one eye. For this study, we asked: How well do radial peripheral displays that use multicolor LEDs affect direction estimation performance? (**RQ1**). Given that this was an exploratory study, we did not posit specific hypotheses. However, we expected high performance in direction estimation given the radial nature of the two LED ring displays, where each set of LEDs have an equal distance to the eye. Furthermore, we explored different LED colors to determine the best perceived and most preferred colors for inclusion in our following study (Section 5). Also participants were asked to state whether they saw LEDs on one versus both eyes after each trial. We did not look into search time for the first study since our focus here is on the impact of different colors and directional cues of radial lights rather than the performance of RadialLight in specific use cases like searching for out-of-view objects.

Procedure

For both our experiments, we ran pretests to determine optimal color luminance, choice of input device, and HMD calibration. To ensure LEDs were perceivable but not too bright compared to the backgrounds tested, we relied on the unicolor model [7] to provide the same luminance across all colors. For input device, we tested a modified numeric pad, scroll wheel, and jog dial, where pre-testing showed jog dial was most suitable as it felt natural to indicate direction without requiring looking at a screen. To ensure all participants have their headset centered, we placed a black circular pointer on the lens and smartphone display for calibration purposes.

Participants signed a consent form, and then seated near a desk where they wore our *RadialLight* prototype (Figure 1c). After a short study introduction, participants calibrated the HMD and underwent a tutorial where each of the 6 conditions (blocks) was presented. Thereafter, we tested each condition in one block, resulting in six blocks. For all conditions, we tested all 18 LEDs on both eyes once (1944 trials), and four runs per condition when LED was on for one eye only (two left; two right) (432 trials). This was done based on pretests that showed participants do not perceive such differences. Presentation order was randomized. For each trial, one direction cue is shown to participants for 5 seconds, where the cue duration was empirically determined as suitable. Thereafter, the cue is disabled and the participant has to specify the cue direction with a jog dial (Figure 3a) that controls an arrow on the screen. Experiment sessions lasted approximately 30 minutes.

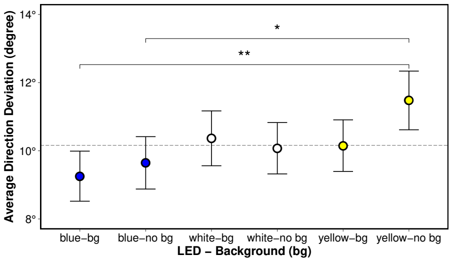


Figure 4: Average error and 95% confidence intervals for direction estimation accuracy. The dashed line marks the average error for all conditions.

Participants

We had 18 volunteer participants[4] (9 females), aged between 21-53 years (M=29.06, SD=4.43). All participants had normal or normal-corrected vision, with no color vision impairments.

Results

We investigated differences in direction estimation accuracy across LED colors, background conditions, and presentation on one vs two eyes. As a Shapiro-Wilk test showed our data is not normally distributed ($W = .90, p < 0.001$), we conducted Wilcoxon rank-sum tests to check for significant effects for each of our IVs on direction estimation accuracy.

LED color. The average deviation (error) for direction estimation was 10.16° ($SD = 7.79$). A pairwise Wilcoxon test with Holm-Bonferroni adjustments revealed that the average deviation for *blue* colored LEDs was significantly lower than for *yellow* colored LEDs ($W = 82368, Z = -3.37, r = .12, p < .01$). Median error for both conditions was the same ($MD = 10, IQR = 10$) and the means differed by 1.36°. These show that while all colors performed well in cueing direction, the blue LED color had the lowest error.

Background. A Wilcoxon Rank Sum test did not reveal any significant differences between background ($M = 9.92$, $SD = 7.63$) and no background ($M = 10.40$, $SD = 7.95$) across all colors ($W = 235500, Z = 1.00, r = 0.03, p = 0.27$), which shows that a plain background did not influence user's direction estimation accuracy.

LED x Background. A pairwise Wilcoxon test with Holm-Bonferroni adjustments showed significant differences in direction estimation accuracy between *blue-background* and *yellow-no background* ($W = 19240, Z = -3.89, Z = .10, p < 0.01$). Furthermore it showed significant differences in direction estimation accuracy between *blue-no background* and *yellow-no background* ($W = 20510, Z = -3.09, r = .08, p < .05$). Figure 4 shows the average deviation and 95% confidence intervals of input error (degrees) for LED colors across background conditions. This supports our earlier finding that blue LEDs outperform other colors, irrespective of background.

One vs. two eyes. We looked into differences in average direction deviation for cues presented to one ($M = 10.66, SD = 8.36$) or two eyes ($M = 10.05, SD = 7.66$) simultaneously. To handle sample imbalances for LEDs shown on one versus two eyes, we downsampled the two eyes group (N=1944) to the one eye group sample size (N=432). We used random downsampling without replacement and tested differences (Wilcoxon signed-rank test) in direction error across 1000 sampling runs (seeds)[5] To combine probabilities, we used Fisher's method[6] [5]. When p-values tend to be small, the test statistic X^2 will be large, which suggests the null hypotheses are not true for every test. Here again, we found no statistically significant difference between one versus two eyes (χ^2(1, N=2,000) = 2038.26, p=0.27). Furthermore, only three participants noticed differences between eye conditions, where they stated they saw the LED light only on one eye (18/432, 0.04%), of which they were correct only 0.02%. These findings indicate that LEDs shown on one vs two eyes simultaneously does not affect direction estimation accuracy nor subjective experience.

STUDY II: CUE DIRECTION AND SEARCH IN 360° VIDEO

In a second study, we ask how *RadialLight* performs with respect to cue directional accuracy and out-of-view object search time performance in two 360° video VR scenarios (car cockpit, ship bridge) (**RQ2**)?

To ensure external validity, we tested *RadialLight* in two 360° video scenarios (car cockpit, ship bridge) using blue LED color for direction cues. We measured directional accuracy and cue search time for out-of-view objects. The scenarios can be seen in Figure 5. The ship bridge consisted of a tugboat and surrounding water. Most parts of this video were simply bluish without much to see. The car cockpit on the other side, included pedestrians walking on left and right sidewalks and oncoming vehicles.

Study design

Given we observed no significant differences across LED colors in Study I, we chose blue LEDs to represent directional cues as they showed lowest error on average. Similarly to Study I, our second study was designed as a lab study and took place in the same environment. Our experiment consisted of two tasks and followed a repeated-measures design with 360° video as independent variable with two levels: car cockpit vs. ship bridge scenario. Both scenarios gave a first person experience of either a ship moving, or a car moving (with pedestrians and activity on the road). First task was direction estimation where our dependent variable (DV) was cue directional accuracy, and second was an out-of-view object search task where our DV was search time performance.

Task 1: Direction estimation. The first task was similar to Study I's estimation task, however here we changed the levels of our independent variable (IV) to ship bridge and car cockpit 360° videos (see Figure 5). We measured the angle deviation between the LED position and the user's subjective assessment.

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[4] Based on a Latin-square design with six conditions. For mean effect sizes of (f = 0.20), at least 164 observations are necessary, which requires testing at least 9 participants.

[5] Since p-value combination under Fisher's method follows a X^2-square distribution, we needed a minimum of 220 runs to achieve 0,95 power and 0.3 effect size under α=0.05.

[6] This is a common method used for aggregating probabilities, however we tested other methods (e.g., voting) and results did not differ.

(a) 360° video ship bridge snapshot. (b) 360° video car cockpit snapshot.

Figure 5: 360° video scenarios. *Best seen in color.*

Task 2: Out-of-view object search. For this task, we randomly distributed virtual objects (occupying 5° of 20° directional view) in exactly 90° out of view. For each LED, we show one object. IVs were the same as in the first task. We measured search time for locating an out-of-view object.

We asked: How well does *RadialLight* perform with respect to cue directional accuracy and out-of-view object search time performance in 360° video scenarios? **(RQ2)**. Given our exploratory work, here again we did not posit strict hypotheses. However, we expected that the car cockpit scenario would be more distracting because of pedestrians and oncoming vehicles and therefore result in lower performance across each task than the ship bridge scenario.

Procedure

Procedure of this study was identical to Study I, except for the following: we showed only blue LEDs for directional cues and we let users experience our two 360° video scenarios (car cockpit, ship bridge) instead of backgrounds. Afterwards, they indicated direction using the jog dial (Figure 3a). For the search task, users followed a similar procedure, however here they had to only turn their head to locate the cued out-of-view object (Figure 3b), and upon finding it, the object disappears. Participants had a cursor representing their gaze. The participants were asked to use this cursor to select the out-of-view object. Time stopped when participants successfully selected the out-of-view object. Afterwards, a participant faces front, and the next trial begins.

Participants

We had 12 volunteer participants[7] (4 females), aged between 21-38 years (M=26.75, SD=4.43). All participants had normal or normal-corrected vision, with no color vision impairments.

Results

We looked into the effect of 360° video VR scenarios (car cockpit, ship bridge) as backgrounds to ensure ecological validity in cue direction estimation accuracy. Furthermore, we measured search time performance. A Shapiro-Wilk test showed our data on direction estimation accuracy ($W = 0.82, p < 0.001$) and on search time performance ($W = 0.82, p < 0.001$) is not normally distributed, and thereafter we conducted Wilcoxon rank-sum tests to check for significant effects of our IV on direction estimation accuracy and search time performance.

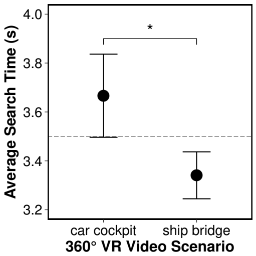

Figure 6: Mean selection time performance and 95% confidence intervals. The dashed line marks the mean selection time performance for all conditions.

360° VR scenario: Direction Estimation. The average deviation for direction estimation for the car cockpit scenario was 11.8° ($SD = 10.58$) and 11.2° ($SD = 9.48$) for the ship bridge scenario. We found no significant effect of scenario on direction estimation accuracy using a Wilcoxon rank-sum test ($W = 12746, Z = 0.70, r = 0.03, p = 0.45$), which shows that cue direction is identifiable irrespective of the tested scenarios.

360° VR scenario: Search Time.

However, there was a significant effect on search time performance ($W = 20042, Z = 2.06, r = 0.09, p < .05$), which shows that a more distracting environment such as a first person experience in a moving car slows users in finding out-of-view objects. Figure 6 shows the average direction deviation and its 95% confidence intervals for car cockpit ($M = 3.67, SD = 1.38$) and ship docking ($M = 3.34, SD = 0.78$) scenarios.

IMPLICATIONS

Our work has implications for building peripheral HMDs and for designing peripheral directional cues:

Radial peripheral LEDs suitable for directional cueing. From both studies, we observed that every direction was perceived with nearly the same average angle deviation (i.e., no significant differences observed), which indicates that radial LED placement for encoding direction towards out-of-view objects is a suitable approach **(R1)**.

LED color does not strongly affect performance. While we found in Study I that blue LED color resulted in lower direction estimation error than the other tested colors (white, yellow), the highest average error observed is still low (<12°). This indicates that choice of peripheral LED color does not strongly affect user performance for direction estimation tasks.

Radial monocular display sufficient for binocular vision. Participants did not recognize the difference between LEDs shown to one eye versus both eyes, where direction accuracy using *RadialLight* was not significantly affected. This shows having a single monocular display with a single LED switched on is sufficient for peripheral direction cueing, which helps reduce power consumption and cost of such displays.

360° VR Scenario complexity increases object search time. While average direction deviation differences between the ship bridge (11.2°) and car cockpit (11.8°) scenarios showed no significant effects, search time performance for locating out-of-view objects was affected. While we only tested two

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[7] For mean effect sizes of (f = 0.20), at least 164 observations are necessary, which requires testing at least 9 participants. We calculated this value with G*Power under Wilcoxon signed-rank test ($\alpha = 0.20$ and $1 - \beta = 0.80$).

360° video scenarios, this effect on search time may be more pronounced across more distracting scenarios or with increasing user engagement (e.g., in a ship monitoring situation) **(R2)**.

Limitations

Since we place LEDs in the periphery of users, light reflections experienced when wearing *RadialLight* should be avoided. Although we took measures to avoid this (e.g. using black tape around LEDs), some reflections occurred as stated by participants (1.3% of cases, N=2914). This however did not affect estimation performance. Also, we did not test multiple LED color combinations within a task, however based on related work (cf., [4]), we believe participants can easily distinguish between colors due to radial LED placement. Finally, we only investigated 360° video scenarios, and not more engaging VR scenarios (e.g., games where the user is involved). While this was beyond the scope of our work, we suspect user performance will generally drop as a function of engagement.

CONCLUSION

We introduced *RadialLight*, and explored LED-based directional cueing for locating out-of-view objects. Evaluating *RadialLight* in two user studies, our findings highlight the usefulness of directional cueing in such peripheral displays and in expanding the FOV in HMDs (cf., [12]). While we evaluated our system in 360° video VR scenarios, we believe our results are more generally applicable to AR, VR, and mixed reality environments. In future work, we want to compare our approach to an on-screen visualization that obviates the need to add extra hardware to the HMD.

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