Investigating a Sparse Peripheral Display in a Head-Mounted Display for VR Locomotion *(submission ID = 1351)*

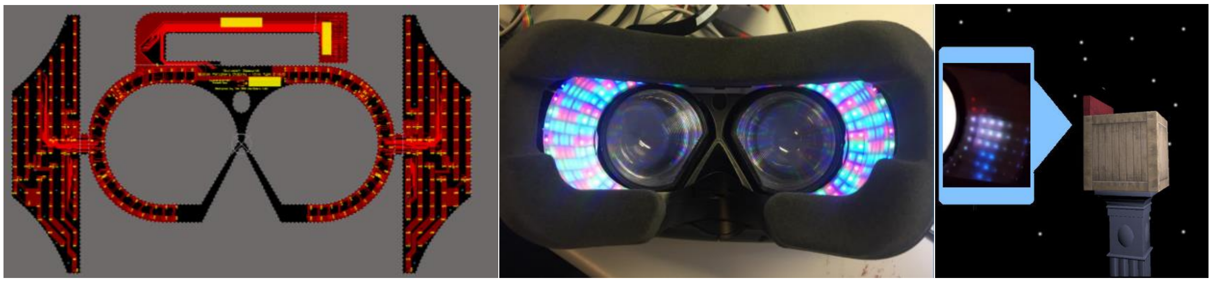

Figure 1. (Left) The layout of the flexible circuit board containing 256 RGB LEDs for the SPD. (Middle) The assembled HTC Vive VR headset with the SPD turned on with random colours. (Right) The close-up image from the SPD, while showing the extended view of a virtual environment.

ABSTRACT

Head-Mounted Displays (HMDs) provide immersive experiences for virtual reality. However, their field of view (FOV) is still relatively small compared to the human eye, which adding sparse peripheral displays (SPDs) could address. We designed a new SPD, *SparseLightVR2*, that increases the HMD's FOV to 180° horizontally. We evaluated *SparseLightVR2* with a study (*N*=29) by comparing three conditions: 1) no SPD, where the peripheral display (PD) was inactive; 2) extended SPD, where the PD provided visual cues consistent with and extending the HMD's main screen; and 3) counter-vection SPD, where the PD's visuals were flipped horizontally during VR travel to provide optic flow in the opposite direction of the travel. The participants experienced passive motion on a linear path and reported introspective measures such as sensation of self-motion. Results showed, compared to no SPD, both extended and counter-vection SPDs provided a more natural experience of motion, while extended SPD also enhanced vection intensity and believability of movement. Yet, *Visually induced motion sickness* (VIMS) was affected by display condition. To investigate the reason behind these non-significant results, we conducted a follow-up study and had users increase peripheral counter-vection visuals on the central HMD screen until they nulled out vection. Our results suggest extending HMDs through SPDs enhanced vection, naturalness, and believability of movement without enhancing VIMS, but reversed SPD motion cues might not be strong enough to reduce vection and VIMS.

Keywords: Virtual reality, wide field-of-view, sparse peripheral display, peripheral vision, vection, navigational search task.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems –Artificial, augmented and virtual realities;

1 INTRODUCTION

Head-mounted displays (HMDs) for virtual reality (VR) have the power to immerse people into another world without having to leave the comfort of their chair. Yet, one challenge even the latest generation of HMDs face is their relatively small field of view (FOV) compared to human unrestricted vision, which reduces their awareness of the surroundings. Especially during travel in VR, increasing the FOV has been shown to enhance the self-motion sensations, also known as vection [1], but it also induces *Visually induced motion sickness* (VIMS) [2]. VIMS feels similar to regular motion sickness, but happens typically when the user is stationary or limited in movement. Therefore, our research problem was how to increase FOV of HMD without enhancing VIMS during travel.

Humans naturally have a horizontal FOV (HFOV) of slightly over 210°, but binocular vision, or depth perception, happens only in the 114° central HFOV. However, there is a much higher concentration of motion-sensitive cells on eye periphery [3], which are not affected by current HMDs such Oculus Rift or HTC Vive due to their relatively small FOV (about 90° FOV). Designing HMDs with large FOV seems challenging in terms of display accuracy [4], therefore, a low-cost way to provide peripheral visuals is to mount small, flexible low-resolution RGB LED array inside the HMD's sides, which was recently presented as a "sparse peripheral display" (SPD) for Oculus-Rift DK-2 HMD, called *SparseLightVR* [5]. In this work, we designed an enhanced version, called *SparseLightVR2* for HTC Vive HMD (Figure 1-Left and Figure 1-Middle), which provides higher resolution in the periphery, while also better matching the main HMD brightness range. In order to extend the FOV of HMD without enhancing VIMS during travel, we evaluated two types of visuals for SPD:

1. Extended SPD, where PD shows visuals consistent with and extending HMD's main screen (Figure 1-Right) to increase its FOV. We hypothesised that extended PD visuals enhances vection.
2. Counter-vection SPD, which is similar to extended view when the user is not traveling in VR. But when the user starts travel, the visuals will be flipped horizontally, which means that all the image pixels on the PD, where should be shown from left to right, are shown from right to left. For example, when the user moves forward, the peripheral objects moves forward (instead of backward). This reverse motion counters only the user's motion caused by the controller input not the natural body or head rotation. We hypothesised that counter-vection PD visuals null vection and thus cancel VIMS, because researchers suggest that vection is a necessary (but not sufficient) prerequisite of VIMS [6].

Xiao and Benko showed higher situational awareness for extended-SPD of *SparseLightVR* [5], but gave promising yet mixed results for VIMS reduction with counter-vection SPD, and higher user preference ratings for *SparseLightVR* compared to no-SPD, *i.e.,* a normal HMD. Yet, our work fills following gaps of [5]:

1. In [5], the counter-vection visuals were provided by black-white strips added to PD visuals moving in the opposite direction of the travel. As some participants reported these black-white bars are

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distracting [5], we replaced them horizontal flipping of PD visuals, which are with less distracting, and more naturalistic visuals that can be generalized for all environments;
2. Assessing additional user experience aspects, such as presence, vection, immersion, naturalness, and believability of movement;
3. We ran another study to better understand why counter-vection-SPD could not null vection, and thus VIMS.

2 METHODS

Study 1: To investigate how different SPD visuals affect VR locomotion measures (including vection, VIMS, naturalness and believability of movement), twenty-nine participants (13 F, 16 M, 19 to 66 years of age, mean 27.8) took part in our within-subject experiment. They were asked to report vection during passive motion on a linear path (Figure 2-Left) with three conditions: extended-SPD; counter-vection SPD; and no-SPD, similar to a regular HMD with no PD visuals in Latin-square order. VIMS was measured by Kennedy's Simulator Sickness Questionnaire (SSQ) before and after the study. After each trial, participants also rated vection intensity and naturalness of movement by continuous scale of (0-100%), and believability of movement by Likert-scale ratings between [-5, 5].

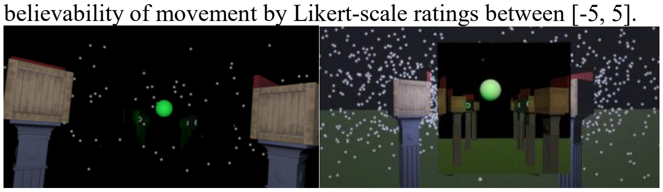

Figure 2. Left) Study 1: Passive motion along a linear path between boxes and fireflies. Participants needed to report when they felt vection. Right) Study 2: Participants see what is behind them through a simulated mirror, and see what is in front of them through a window in the mirror center. They needed to adjust the window FOV to null vection.

Results: After excluding one participant due to data inconsistency, a repeated-measures ANOVA revealed a significant effect of PD visuals on vection intensity, F(2, 54) = 7.50, p = .001, η_p^2 = .217, naturalness of motion, F(2, 54) = 7.71, p = .001, η_p^2 = .222, and believability of motion, F(2, 54) = 3.510, p = .037, η_p^2 = .115. Tukey-HSD post-hoc test showed that extended SPD yielded significantly higher vection intensity (p = .001) and believability of motion (p = .038) compared to no SPD. Moreover, both extended and counter-vection SPDs yielded significantly higher naturalness ratings compared to no SPD (p's < .01) as illustrated at Figure 3. However, no significant effect was found on presence, preference, and VIMS.

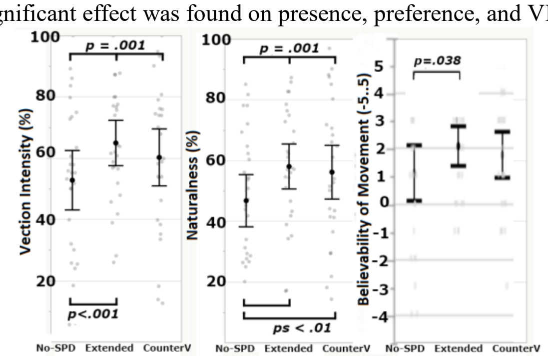

Figure 3. Study 1 Results - Average perceived vection intensity (left), naturalness of movement (middle), and Believability of motion (right) for each PD mode. (CI = 95%).

Study 2: Because our experimental results showed no significant effect of counter-vection peripheral visuals on vection as well as VIMS, we hypothesised that providing counter-vection visuals only on the PD might not be enough to null vection or reduce it significantly. To test this hypothesis, we conducted a within-subject follow-up study to measure how much counter-vection visuals are needed to null the vection. To provide natural counter-vection visualson HMD's main display, we simulated a mirror in front of the user that shows what was behind them during forward linear motion, similar to a rear-view mirror that reverses the optic flow direction. A window in the center of the mirror showed the user what was in front of them, so that they saw the forward scene in the center of HMD screen and counter-vection visuals at the periphery of the HMD screen (see Figure 2-right). Fifteen participants experienced passive forward motion on a linear path, and were asked to control the amount of vection vs counter-vection visuals by changing the size of the center window, to null vection, until they feel moving neither forward nor backward.

Results: The results show no significant effect of counter-vection visuals on different PD visuals. The minimum respective maximum FOV reported by participants was between 13°-46°, which shows that counter-vection cues displayed only on the SPD were not strong enough for any participants.

3 DISCUSSION AND CONCLUSION

The extended SPD appears promising, in terms of providing stronger vection, naturalness and believability of movement, while at the same time not significantly increasing motion sickness, which was a concern from using a wide FOV display. Post-experimental interview also showed that the extended SPD was like driving on a highway at night or going into hyper drive with stars whizzing past in the periphery, which seemed more believable and consistent with previous experiences of moving through real world environments.

On the other side, despite providing strong counter-vection visuals by adjusting contrast and speed of counter-vection PD visuals, they did not reduce vection or VIMS significantly. A follow-up study showed that SPD visuals cannot provide strong enough vection cues compared to the HMD's main display. Therefore, cancelling motion sickness by counter-vection visuals might need stronger visuals, which can be distracting for the user. Alternatively, we can provide counter-vection visuals on part of the HMD's main display as well. Future studies also could investigate how the lack of sensation of self-motion might affect behavioural and other perceptual measures.

Overall, our results suggest using an inexpensive lightweight sparse peripheral display with extended visuals to increase the HMD's field-of-view improves different aspects of the locomotion experience, including a sensation of self-motion, naturalism and believability of movement without enhancing motion sickness.

REFERENCES

[1] S. Nakamura, "The perception of self-motion induced by central and peripheral visual stimuli moving in opposite directions," *Jpn. Psychol. Res.*, vol. 43, no. 3, pp. 113–120, Sep. 2001.
[2] B. Keshavarz, H. Hecht, and L. Zschutschke, "Intra-visual conflict in visually induced motion sickness," *Displays*, vol. 32, no. 4, pp. 181–188, Oct. 2011.
[3] I. P. Howard and B. J. Rogers, *Binocular Vision and Stereopsis*. Oxford University Press, 1995.
[4] J. Orlosky, Q. Wu, K. Kiyokawa, H. Takemura, and C. Nitschke, "Fisheye Vision: Peripheral Spatial Compression for Improved Field of View in Head Mounted Displays," in *Proceedings of the 2Nd ACM Symposium on Spatial User Interaction*, New York, NY, USA, 2014, pp. 54–61.
[5] R. Xiao and H. Benko, "Augmenting the Field-of-View of Head-Mounted Displays with Sparse Peripheral Displays," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 2016, pp. 1221–1232.
[6] B. Keshavarz, B. E. Riecke, L. J. Hettinger, and J. L. Campos, "Vection and visually induced motion sickness: how are they related?," *Front. Psychol.*, vol. 6, Apr. 2015.