vrGazeCore: A toolbox for virtual reality eye-tracking analysis

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Abstract:

Virtual reality (VR) combined with in-headset eye-tracking is a powerful method for studying vision and memory in naturalistic conditions. Using VR, participants actively explore visual environments from a first-person perspective by moving their eyes, heads, bodies. To date, existing software for processing eye-tracking data from VR headsets is proprietary, and often black-boxed to the researchers using it as a result. Here we present vrGazeCore, an open-source toolbox that processes eye-tracking data from 360° VR scenes at both the individual and group levels. The toolbox has a flexible processing pipeline that rectifies raw eye coordinates with head position, determines fixations in a scene, and calculates fixation density maps for a scene, which can later be aligned with models of scene content. In addition, analysis parameters can be tailored to fit the needs of the researcher. In sum, vrGazeCore makes the study of active vision in immersive scenes more accessible by offering a flexible, open-source package for analyzing eye-tracking data from head-mounted VR displays.

Keywords: virtual reality; eye-tracking; toolbox

Introduction

Although eye-tracking studies have provided key insights into many aspects of cognition, traditional eye-tracking paradigms severely limit naturalistic behaviors, requiring head-restricted participants to passively view stimuli on a computer screen. Many studies have shown that naturalistic, active viewing conditions, where subjects are allowed to freely move their eyes, heads, and bodies, impact perceptual processing and visual development (Held & Hein, 1963; Goldberg & Wurtz, 1972; Troncoso et al., 2015; Haskins et al., 2020). However, until recently, limitations in available technology impeded the ability to study naturalistic gaze behavior.

Virtual reality (VR) in combination with in-headset eye-tracking is an increasingly popular solution to study gaze behavior under more naturalistic conditions, as it allows participants to freely move their head and bodies as they would in real life, while also maintaining experimental control (Haskins et al., 2020; Haskins et al., 2022). However, eye-tracking in VR poses some unique challenges compared to more standard eye-tracking paradigms, which assume the participants are head-fixed and the stimuli occupy only a portion of the visual field. To date, current software that is available to process in-headset eye-tracking data is proprietary and often black-boxed from researcher control as a result, placing limitations on the flexibility of analysis.

Here we present vrGazeCore (https://github.com/Robertson-Lab/vrGazeCore-Toolbox), an open-source toolbox for both individual- and group-level analysis of eye-tracking data collected from 360° VR environments. The toolbox addresses the challenges of freely moving heads and immersive stimulus presentation by rectifying the eye-position and head-position data from the in-headset eye-tracker to determine gaze coordinates in 360° space. vrGazeCore is also able to provide additional gaze-derived measures, including fixation metrics, trial-averaged fixation density maps, and data visualizations that can later be integrated with visual models of the content a 360° stimulus. It has demonstrated high precision and accuracy of fixations across two eye-tracking VR systems: Oculus DK2 Pupil Labs (accuracy: 2.00 DVA +/- 0.38 STE; precision: 0.26 DVA +/- 0.05 STE) and HTC Vive Eye (accuracy: 2.63 +/- 0.27 STE; precision: 0.16 +/- 0.08 STE). Its open-source nature makes it easily accessible and allows users full flexibility over their analysis.

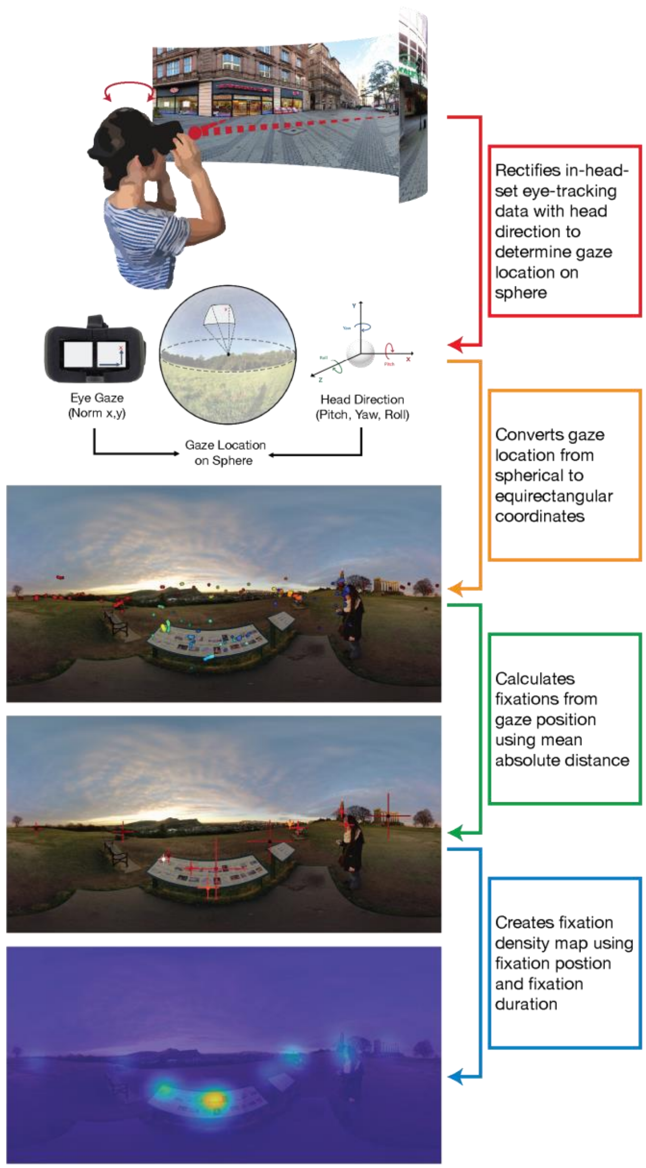

Figure 1. vrGazeCore uses the raw in-headset eye-tracking data from a VR experiment and rectifies the eye gaze data with head position to determine gaze location on a sphere. The gaze points (dots) are transformed into equirectangular coordinates, from which fixations (crosshairs) and fixation density maps can be calculated.

The vrGazeCore Processing Pipeline

vrGazeCore uses the raw eye- and head-positions from the in-headset eye-tracker as input (Fig. 1). Users can apply a variety of quality control measures, including filtering based on eye-tracker confidence, to the data at this stage. To determine where the gaze lies in the 360° environment, vrGazeCore then rectifies the raw eye-position data (in normalized screen coordinates) with head-position data (pitch, yaw, and roll) to produce gaze location in 360° spherical coordinates (Fig. 1). For further processing, it converts the spherical coordinates to an equirectangular projection.

To determine where subjects are fixating, vrGazeCore calculate fixations using the location of the gaze and the mean absolute deviation (MAD) of distance in degrees per second over a sliding window (Voloh et al., 2020). The threshold to classify a potential fixation, along with other parameters, can be set by the user, although reasonable default values are including. Fixations are validated and saved for each scene and subject.

vrGazeCore can also create fixation density maps from the valid fixation data to visualize how subjects viewed the areas of the 360° scene and potentially compare it to other maps (e.g., semantic map of scene). It weights each fixation on the scene by its duration and applies a variable-width gaussian filter, scaled by the latitude of the fixation point, to create the density map. The toolbox can create fixation density maps at different timepoints during a scene, to analyze how fixation density changes over the viewing duration. It can also create fixation density maps at the group-level, allowing for comparison between different subject groups.

Results of vrGazeCore

vrGazeCore outputs the fixation coordinates and durations for each scene and subject, along with the raw gaze-points that underlie each fixation and the raw eye-tracking data from the in-headset eye-tracker. Additionally, it can optionally plot a variety of gaze-derived data over the equirectangular projection of a scene, including the raw gaze points, raw head movement, fixations, and a combination of the three (Fig. 1). vrGazeCore also saves the fixation density maps as a matrix of values and can optionally overlay the map onto the scene, so that the data can be visualized and analyzed with reference to immersive scene content (Fig. 1).

Conclusions

vrGazeCore processes in-headset eye-tracking data in an open-source and fully adaptable way. The toolbox makes analyzing data from active vision VR studies more accessible, promoting the use of naturalistic paradigms to study gaze and its insights into cognition.

Acknowledgments

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