Finding landmarks – an investigation of viewing behavior during spatial navigation in VR using a graph-theoretical analysis approach

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Vision provides the most important sensory information for spatial navigation. Recent technical advances allow new options to conduct more naturalistic experiments in virtual reality (VR) while additionally gather data of the viewing behavior with eye tracking investigations. Here, we propose a method that allows to quantify characteristics of visual behavior by using graph-theoretical measures to abstract eye tracking data recorded in a 3D virtual urban environment.

The analysis is based on eye tracking data of 20 participants, who freely explored the virtual city Seahaven for 90 minutes with an immersive VR headset with an inbuilt eye tracker (Fig. 1a). To extract what participants looked at, we defined “gaze” events (Fig. 1b), from which we created gaze graphs (Fig. 1c). In these gaze graphs, nodes represent houses while edges represent their visual connection, i.e., gazes in direct succession on the respective houses. Thus, the gaze-graphs capture relevant spatial information gathered during exploration. On these graphs, we applied graph-theoretical measures to reveal the underlying structure of visual attention.

Applying graph partitioning, we found that our virtual environment could be treated as one coherent city. To investigate the importance of houses in the city, we applied the node degree centrality measure (Fig. 2a). The node degree centrality graph measure reveals a surprisingly large variance. However, the values of individual houses were rather consistent across subjects, as shown by the high mean correlation. Additionally, we observed that the degree distribution across houses increased steadily, except for only a few high node degree houses. Specifically, our results revealed that 10 houses had a node degree that exceeded consistently two-sigma distance from the mean node degree of all other houses (Fig. 2b). The importance of these houses was supported by the hierarchy index, which demonstrates that the frequency of houses decreased drastically with increasing node degree, revealing a clear hierarchical structure of the gaze graphs. As these high node degree houses fulfilled several characteristics of landmarks, we named them “gaze-graph-defined landmarks”. Applying the rich club coefficient, we found that these gaze-graph-defined landmarks were preferentially connected to each other (Fig. 2c). Furthermore, participants spent the majority of their experiment time in city areas, where at least two of those houses visible and thus could allow triangulation for spatial localization.

Overall, our findings do not only provide new experimental evidence for the development of spatial knowledge, but also establish a new methodology to identify and assess the function of landmarks in spatial navigation based on eye tracking data.
Figure 1: (a) Experimental setup during VR exploration in the virtual city Seahaven. (b) Time line of gaze events by a participant. The abscissa represents the first 30 seconds (900 hit points) of the recordings. The ordinate contains all viewed houses viewed during that time line. In this panel each house has a distinct color for visualization only. (c) The graph corresponding to the time line of panel B is visualized on top of the map of Seahaven. The colors of the nodes match the colors of the boxes in panel A. Edges are labelled according to the order they were created.

Figure 2: (a) The graph of one participant is visualized on top of the map of Seahaven. The nodes were colored according to their respective node degree centrality. (b) The mean node degree distribution across all subjects with mean, 1σ- and 2σ-thresholds. (c) The development of the rich club coefficient with increasing node degree. The dot-lines are the rich club coefficients of individual participants, while the green line is the mean across all subjects.