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Spatial Perception in Immersive Visualization: A Study and Findings

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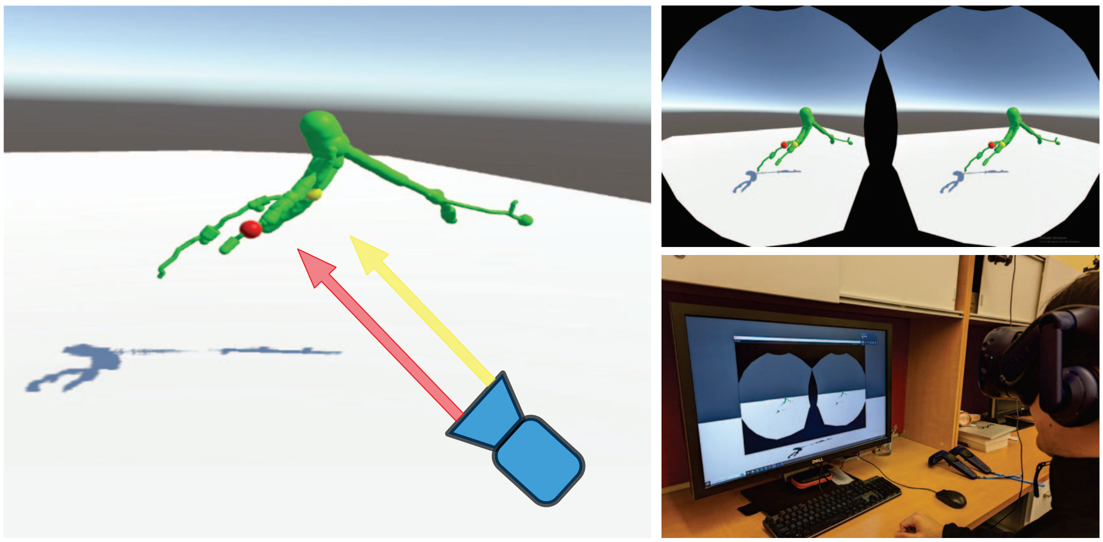

Figure 1: We design and conduct an experiment to investigate the influence of two different depth cues on users' depth perception in virtual reality (VR). The left figure is an illustration about the user's task in the experiment, comparing the red and yellow sphere's depth relative to the VR camera. The right top view is the binocular view in VR. The right bottom is to show the experiment environment.

Abstract

Spatial information understanding is fundamental to visual perception in Metaverse. Beyond the stereoscopic visual cues naturally carried in Metaverse, the human vision system may use other auxiliary information provided by any shadow casting or motion parallax available to perceive the 3D virtual world. However, the combined use of shadows and motion parallax to improve 3D perception have not been fully studied. In particular, when visualizing the combination of volumetric data and associated skeleton models in VR, how to provide the auxiliary visual cues to enhance observers' perception of the structural information is a key yet underexplored topic. This problem is particularly challenging for visualization of data in biomedical research. In this paper, we focus on immersive analytics in neurobiology where the structural information includes the relative position of objects (nuclei / cell body) in the 3D space and the spatial measurement and connectivity of segments (axons and dendrites) in a model. We present a perceptual experiment designed for understanding the consequence of shadow casting and motion parallax in the neuron structures observation and the feedback and analysis of the experiment are reported and discussed.

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Index Terms: Human-centered computing—Visualization—Visualization techniques; Human-centered computing—Visualization—Visualization design and evaluation methods

1 Introduction

When stepping into metaverse, one of the engaging attributes is the realistic spatial perception people can obtain. We are able to understand the situated environment thanks to our sensory systems, such as the visual cues, audio cues, etc. Similarly, spatial information in metaverse is perceived based on combination of multiple sensory signals, including vision, touch, hearing, etc. In the immersive visual analytics, researchers mainly rely on visual information to observe and understand the topology and morphology of the data and models. Furthermore, when examining multi-dimension information in the immersive environment, people prefer the data investigation methods with minimal mental workload. To this end, optimizing the multi-dimensional data visualization in an immersive environment to efficiently deliver the spatial information (i.e., topology and morphology) is a key topic for popularizing the immersive visual analytics. This problem has been studied for traditional display systems. Beyond the information expressed in the two dimensions of a view in a desktop display system, motion parallax [15, 17] and shadow casting [1, 12] are two of the commonly used methods for providing depth cues as the third dimensional information. On the contrary, spatial information visualization technique for immersive environments has not been fully explored.

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Although an immersive environment can naturally provide the spatial perception for users, we are particularly interested in how the motion parallax and shadow casting methods can facilitate users' spatial information understanding. Specifically, we focus on the auxiliary cue adoption in the neuron structure visualization. In this research domain, neuron scientists examine brain and neuron structures for topological and morphological relationship between multiple segments of the data. Because of the high complexity of the neuron structures and inevitable occlusions between substructures, deciphering the spatial relationship between neuron structure segments is extremely challenging. To the best of our knowledge, there has not been any practical method focusing on the spatial understanding enhancement.

In this paper, we will present a perceptual experiment designed for investigating the effect of two auxiliary methods in visualizing the depth information in neuron structures. Specifically, the related work is discussed in Section 2, the experiment design and result is reported in Section 3, and the discussion and future work is summarized in Section 4. We will release our perception experiment's implementation and experiment data in the project webpage.

2 Related Work

Our focus is the visualization techniques for facilitating neuron researchers to understand the spatial information in the neuron structures. Therefore, our literature summary is structured as the visual representation for neuron structures and the visual cues for depth perception. In Section 2.2, we discuss the existing findings regarding the visual cues for 2D views and stereoscopic views respectively.

2.1 Visualization for neuron structures

Neuron scientists are interested in the topological and morphological information embedding in the 3D structures of neuron cells. With the progress in data acquisition and extraction techniques, the realized information from the neuron structures results in a surge of data dimension and complexity. Consequently, 3D exploration becomes challenging as the branching morphology of an object grows in complexity. Due to these challenges, domain scientists often prefer a simplistic schematic representation [8, 20]. Recent works [2, 13] have introduced methods to alternatively represent dense neuronal structures as abstracted diagrams, albeit in a linear graph-like arrangement. In addition to the planar representation for treelike structures, Hu et al. [5] present an exploration-based visualization method for understanding the geometry information in the original 3D space of the structure.

2.2 Visual cues for depth perception

Enhancing the depth cues in a camera view for a 3D structure has been studied for decades [7, 11, 16]. Motion parallax is used by our brain to perceive the depth information. The perspective transformation of the retinal image produced by the relative movement between the observer and the object is found to be a reliable impression of the relative depth [17]. Nawrot et al. present a formula to link the object shape to the computation of the depth in motion parallax [14].

On the other hand, the shadow can also be informative about the shape of the object, especially when the shadow is in motion [10]. Usability of directional shadows and illumination on the perception of a geometrical scene is well studied [4, 6, 19]. Lindemann et al. [9] evaluate the impact of the wide range of available illumination models on user perception. They find that directional globally affecting shadows, such as shadow volume propagation can improve user during depth estimation and size comparison tasks comparing to Blinn-Phong model and spherical harmonics. For depth estimation task, they find a smaller difference when using shadow volume propagation and directional occlusion shading comparing to Blinn-Phong model or dynamic ambient occlusion.

Thanks to the development in virtual reality (VR) and augmented reality (AR), the VR/AR display systems can provide stereoscopic views. However, the stereoscopic views mainly rely on the binocular disparity to reflect depth information, still lacking the solution for the vergence-accomodation conflict. With this hardware configuration, how well VR users perceive the objects in different depth needs to be investigated. Furthermore, can we still apply the existing depth cues to enhance depth perception? Depth perception in different AR facility is studied in [1]. They found that the depth perceived in video see-through displays is underestimated than the optical see-through displays. In VR, the influence of screen distance, environment richness, and display factors are examined to see both their advantages and disadvantages in [18].

3 Perceptual Experiment

Our target is to investigate how to provide effective depth cues to enhance the spatial understanding in the immersive neuron structure visualization. We start with designing an perceptual experiment to investigate what existing depth enhancement benefits the depth understanding in the immersive environment. Our *null hypothesis* is: the two depth cues, shadow casting and motion parallax, VR users' depth perception performance does not show a significant difference in neuron structure visualization.

3.1 Experiment design

We design an perception experiment using three datasets of neuron structures to test how the shadow casting and motion parallax influence people's judgement of depth particularly in neuron structure examination. Specifically, we refer to the shadow casting and motion parallax as two visualization modes, **Shadow Mode** and **Motion Mode**.

In **Shadow Mode**, one directional light with a fixed direction with Euler angle degrees = $(50, -30, 0)$ was the only directional light source in the virtual environment. Besides, the skybox also exert an ambient light in the environment. Scene objects are shaded in hard and soft shadows.

In **Motion Mode**, the scene object rotate around a vertical axis passing the object's mass center. The rotation is repeated periodically following $\theta = sgn(t) * v_\theta * N$ where θ represents the Euler angle around the vertical axis, $v_\theta = 0.2°$, t is frame number, $N = t\%900$, $sgn(\cdot)$ is a sign function and $sgn(t) = 1$ when $(t/900)\%2 == 0$ otherwise $sgn(t) = -1$.

Visual stimuli In each experiment trial, we rendered a neuron structure's treelike skeleton in the immersive environment with either shadow casting or spinning around the vertical self axis. Meanwhile, two randomly selected nodes in this structure are rendered as red and yellow respectively. The user will be asked to compare the depth of each selected node relative to the camera. We plan to study the participants performance (i.e., correct answer ratio) in order to evaluate the two visualization modes. The neuron structures are rendered in green because in the data acquisition process in neuron science it is common to see the neuron structure dyed in green in the wide-field microscope. The two selected nodes highlighted in red and yellow were shown to the subject (see Fig. 4). The camera view to observe the structures is vital for the geometry information perception. To be fair, camera viewing direction for each dataset is randomly generated and the distance between the camera and the center of the structure is determined using the half distance between the furthest two nodes in the structure. The experiment scenes are shown in Figure 3. Figure 2 shows a dataset in **Motion Mode** (without shadow).

Apparatus We use HTC Vive Pro as the VR device in our experiment. The experiment is designed in Unity®2021.3.4f1. The experiment is running in 90 FPS in a machine with (Intel(R) CPU, Xeon(R) Gold 6242 CPU 2.80GHz 2.79 GHz), 128GB RAM, and a single GPU Quadro RTX 6000.

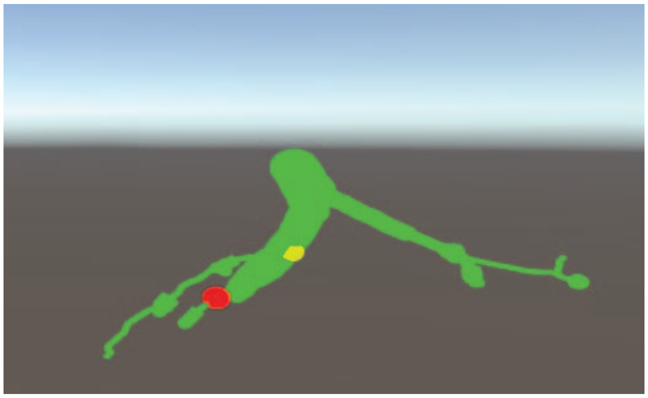

Figure 2: A neuron structure example of the shading without shadows.

Subjects and Dataset Participants are all within the age range (25-34), with 2 females and 3 males. Two of them seldom used VR techniques and three used VR quite often. All the neuron structure data are from the Diadem dataset [3].

Process In the beginning of this experiment, an instruction and description of the experiment were given, followed by a warm-up session. In the formal experiment, every participant wore the headset and observed the neuron structures. In each dataset, four trials were shown to the user sequentially. The order of trials are randomized among participants. The task of each trial is to indicate which node is closer to the subject in the virtual environment. Participants were asked to verbally indicate which sphere is closer to the participant him/her self in each trial. Participants are free to take a rest after each experiment trial and were free to terminate the experiment at any time. Our subject experiment has been approved by the Institutional Review Board at our university.

3.2 Experiment result analysis

Participants took the warm-up session and confirmed the sufficient capability to distinguish the colors, yellow, green, and red in our visual stimuli. All five participants completed all the trials. Since the primary difference between the different trials is the visualization modes: either shadow casting or motion parallax, we conduct the one-way ANOVA to understand if the visualization modes significantly affect users' depth perception. We summarize all participants' incorrect answer numbers in each trial and categorize the answers based on the two visualization modes in Figure 5.

The one-way ANOVA results $p = 0.3282$, the null hypothesis cannot be rejected. The box plots of the result is present in Figure 6. The experiment data will be released in our project webpage. Therefore, based on our current result, we cannot conclude that these two visualization mode significantly affect users' depth perception. On the other hand, the overall correctness of users' answers in motion mode shows the trend that users performed better than in the shadow mode.

3.3 Feedback and discussion

In the post-experiment interview session, one of the participants commented that the shadow may be more helpful if plane receiving shadows is closer to the neuron structures. He thought the closer the plane was, the better we could get the geometry information. Two users commented that the soft shadows on the neuron structures helped them to understand the structures' shape, but the shadows cast on the plane produced few benefit. Two participants explicitly mentioned the object rotating assisted him to tell the depths of the spheres. According to our findings, we suggest introducing motion parallax and soft shadow casting into neuron structure visualization in order to enhance observers' depth perception.

4 Conclusion, Limitation and Future Work

We present designed and conducted a user experiment to understand the influence of shadow casting and motion parallax on depth perception. According to the result and feedback in this user experiment, rotation and soft shadow can help observers to understand the relative position of different segments in the structure. On the other hand, the placement of the plane where the shadow is cast on also affects the perception of the neural structure. We suggest introducing motion parallax and soft shadow casting into neuron structure visualization in order to enhance observers' depth perception.

We use green color for the neuron object shading in the experiment. Our experiment design assumes the color's influence on human's depth perception is negligible. Further experiment is needed in order to comprehensively understand the effect from rendering settings.

In VR, depth is perceived by multiple sensory systems. When observing an object in short depth, the binocular vision can comfortably detect the depth. On the contrary, when an object is placed in a far distance, the binocular parallax cue is weak and the object looks more planar than the object closer to the eyes. Hence, the understanding of the spatial information is also influenced by the depth. The research regarding the influence of the depth and the influence of the color and contrast are in our next step of this research project.

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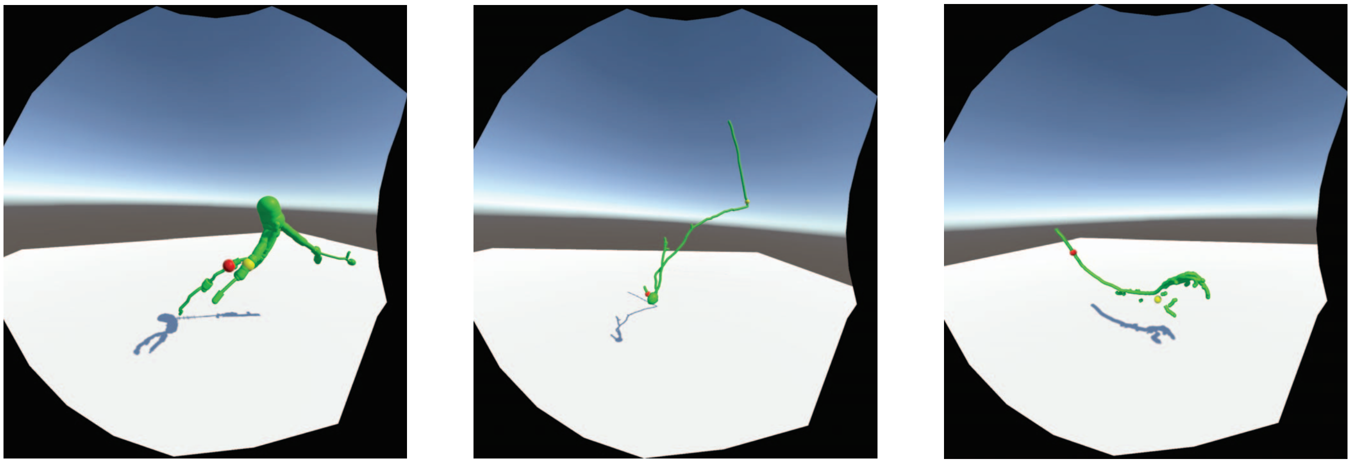

Figure 3: The three subfigures demonstrate the three neuron structures (with shadow casting) in our experiment: Hippocampal neuron structures 1, Hippocampal neuron structures 2, and olfactory neuron structures.

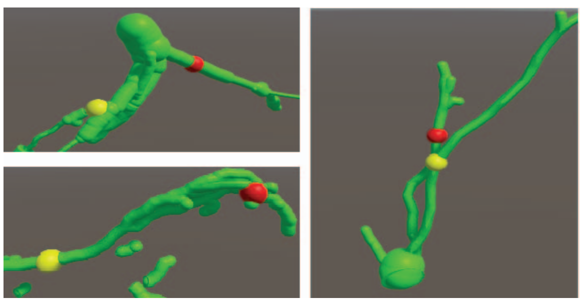

Figure 4: Detailed views about the randomly selected nodes in the structures.

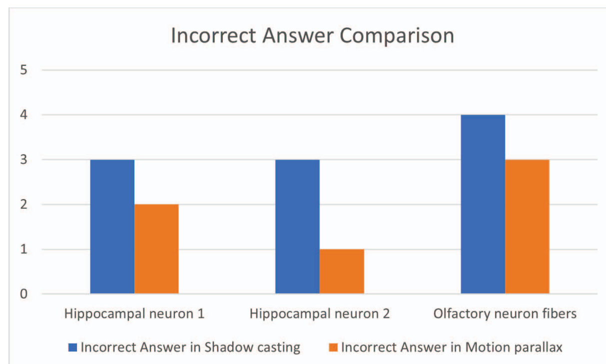

Figure 5: The summary of the incorrect answers in each dataset. The three groups of bars represent the incorrect answer count in the two Hippocampal Neuron structures and the incorrect answer count in the Olfactory neuron fibers, respectively. In each group, the blue bar and the orange bar represent the Shadow mode and Motion mode respectively.

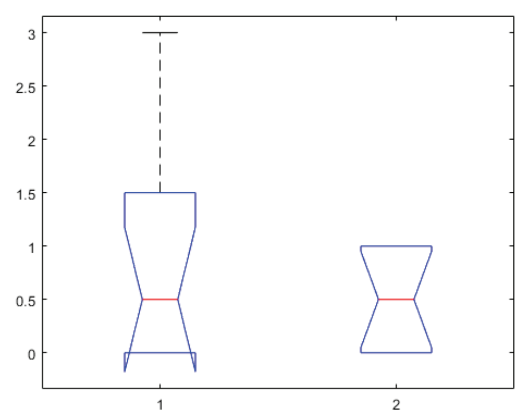

Figure 6: One-way ANOVA result in box plots. The Condition 1 represents the incorrect answers in Shadow Mode and the Condition 2 represents the Motion Mode. The one-way ANOVA shows $p = 0.3282$, the null hypothesis cannot be rejected.

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