Immersive Search: Interactive Information Retrieval in Three-Dimensional Space

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ABSTRACT

Researchers in interactive information retrieval (IIR) have studied and refined 2D presentations of search results for years. Recent advances are bringing augmented reality (AR) and virtual reality (VR) to real-world systems, though the IIR community has done relatively little work to explore and understand aspects of 3D presentations of search results, effects of immersive environments, and the impacts of spatial cognition and different spatial arrangements of results displays in 3D. In the research proposed here, I outline my plan to use immerse environments to investigate how users' spatial cognition may influence the information retrieval process. Specifically, this work will observe how spatial arrangements of search results affect users' ability to find information in the post-query, visual search phase of the IIR process across quantitative and qualitative measures.

CCS CONCEPTS

• Information systems → Search interfaces; **• Human-centered computing → Virtual reality**.

KEYWORDS

immersive search, virtual reality, three-dimensional search

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1 INTRODUCTION AND MOTIVATION

The field of information science has looked at the presentation of search results in two-dimensional interfaces for years. However, rapid advancements in computational power, display technology, and improved tracking mechanisms have moved the immersive technologies of virtual reality (VR) and augmented reality (AR) from the realms of science fiction to real, available tools within the past few years. Head-mounted displays (HMDs) are one such tool that allow humans to immerse ourselves in entirely new worlds or to add virtual objects and information to our natural world. It is the immersion that these technologies are capable of providing that opens up a new dimension of interaction for users and how they might use it to search for information. This area of "immersive search" is still a new area of exploration in interactive information retrieval (IIR) and there are fundamental questions about how the addition of the third dimension can impact how information retrieval is performed by users and how it would be best to present those results to users.

Spatial arrangements are the structuring of virtual objects in 3D space, and spatially arranging information in IVEs can provide a way to engage the non-visual senses in information retrieval. Previous work on information displays in IVEs have shown spatial arrangements of information to aid with recall, path integration, and simple visual search [1, 3, 16]. Beyond those benefits, spatial arrangement of information may prove to be vital when navigating information has to be done without the ability to use one's hands, like a doctor in the operating room.

Spatial cognition is the complex mechanism in which humans acquire, process, and utilize spatial information. It can be engaged through the use of the visual, vestibular, and proprioceptive systems. In traditional computing environments with interactions through a 2D display, such as those on a desktop computer or phone, spatial cognition is activated primarily through the visual system. Many previous efforts to explore the benefits of spatial arrangements of information have been focused on 2D displays and were not designed to engage the vestibular or proprioceptive systems [6, 19]. To the best of my knowledge, few efforts have been made to explore how spatial cognition engaged through immersive technologies could benefit IIR.

In the research proposed here, I hope to gain an understanding of how different spatial arrangements of search results impacts users' interaction with the results. I plan to investigate how arrangements of results designed to engage different aspects of users' vestibular and proprioceptive systems may influence the process of determining if there is a relevant result among a set of results.

2 RELATED RESEARCH

In this section, I review three related areas important to immersive search; immersion and the enabling technologies; spatial cognition - how immersive technology use aids users in construction of a cognitive map of a space; and spatial information displays - how information is displayed around users in an IVE.

2.1 Immersion and Immersive Technologies

Immersion through HMDs can provide the benefit of spatial understanding. Immersion can allow humans to use depth cues like stereopsis and perspective to increase their information bandwidth and

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to facilitate interfaces that reduce information clutter through overlap or occlusion [7]. In addition, immersive virtual environments (IVEs) can engage users' vestibular and proprioceptive systems, which allows us to consider how we can utilize human's innate spatial cognitive abilities to help design more effective information interfaces [16].

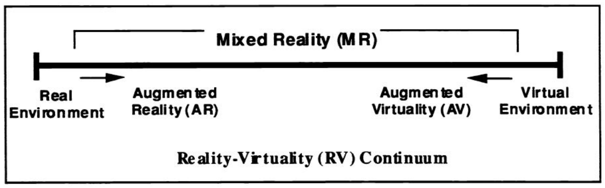

Figure 1: Milgram's Mixed Reality Continuum [17]

Both virtual reality and augmented reality systems can support elements of immersion. Though occasionally discussed as distinct, Milgram's mixed reality continuum [17] (see Figure 1) illustrates the closeness of the two enabling technologies. In my research, I am interested in the opportunities and effects that immersion can play in how search results are presented in both VR and AR environments. I plan to start with VR due its higher field of view than current AR HMDs. But since both VR and AR have some overlapping immersive capabilities, my research looks to study phenomena that are likely to apply to all technologies on the continuum and to understand what immersion means for 3D IIR interfaces.

A study by Pausch, Proffitt, and Williams [18] looked at understanding the quantifiable aspects of immersion. Their study involved a VR environment randomly populated with letters on the walls of a square box that was observable through two conditions: 1) a VR condition where participants used a HMD to view the room and move the camera view, and 2) a desktop display condition where participants used a HMD to view the room and a pointing device to move the camera view. The participants were tasked with finding where a target letter was in a virtual room or identifying if the target letter was not present in the room at all. The authors found no significant time difference between the VR and desktop display conditions on finding the letter when it was present in the room. However, in the VR display condition, participants were significantly quicker at determining when a target letter was not present. The results suggest that when given the ability to use head controls from an ego-centric view point, users are able to sense that they have actually viewed all the spatially situated letters after having completed a movement driven scan of the room.

2.2 Spatial Cognition

Spatial cognition is how humans understand the space around themselves and their place within that space. The process to gain this understanding is through the use of the visual, vestibular, and proprioceptive systems that work together to create a cognitive map of one's environment. There is biological evidence about how head and body movements assist memory recall in humans, owing in part to spatial cells in the hippocampus that allow for recall of representations of environments [13].

The application of spatial cognition in the immersive space can assist with memory tasks. Studies have been performed to determine how IVEs impact memory and how much immersion and/or movement is required to engage those vestibular and proprioceptive senses [11, 15, 16]. Of particular note, Krokos, Plaisiant, and Varshney tasked participants with remembering faces of individuals arranged spatially within a 3D environment. The tasks performed in the VR HMD were designed to leverage the vestibular and proprioceptive systems to enhance users' learning and recall of the faces. The participants interacted with the environment through a traditional desktop computer display or a head-mounted virtual reality display. The results showed that participants had higher recall and fewer errors in the VR HMD condition compared to the traditional 2D display.

Bakker [1] performed experiments to observe the use of different combinations of the visual, vestibular, and proprioceptive systems in navigation of IVEs. The results of this study showed that the engagement of all three systems allowed participants to perform path integration with significantly fewer errors compared to any other combination of the systems. In the learning experiment's short exploration task that compared path integration using immersive and non-immersive conditions, the participants that used the immersive technology showed more accurate knowledge of the environment than those that did not use the immersive technology.

2.3 Spatial Information Displays

Previous work has looked at the spatial organization of data for searching and storage [6, 19]. Other work has also looked at the intersection of information retrieval and spatial concepts to describe and present documents' relevance to each other as a function of space [14, 20]. The findings suggest that users are capable of using spatial arrangements of data and navigating 3D representations of information, resulting in quicker retrieval time and fewer incorrect retrievals in several conditions. My exploratory study will differ by removing the 2D limitation of the traditional computing devices used in those studies and use a VR HMD to immerse the participants in a three-dimensional virtual environment.

Spatial information displays use HMDs to turn the immediate area surrounding the user into an immersive and controllable space for information use. This body-centered spatial information display has been described as the surround-fixed display, the mobile infosphere, the body-stabilized display, and the body-fixed display [4, 5, 9, 10]. Body-fixed information displays are distinct from, but not incompatible with, view-fixed and world-fixed information displays where virtual objects are fixed to the viewpoint of the user or fixed to real (or virtual) world objects, respectively. Instead, this virtual space is centered around the user's body and moves a, they move.

The body-fixed display has been analyzed against a view-fixed display in simple visual searches [3]. Billinghurst's experiment compared how users performed an information search for a target image between a view-fixed condition, a body-fixed condition with hand controls, and a body-fixed condition with head tracking. After normalizing values for system performance, users were shown to have performed significantly faster in the search tasks in the body-fixed conditions. In subjective measures, the participants reported higher satisfaction in the body-fixed conditions and ranked them above the view-fixed condition. Of particular interest to me are the remarks from participants that the head-tracked body-fixed condition allowed them to associate information to a space relative to where they were looking.

3 RESEARCH QUESTIONS

This research explores how users process and interact with virtual information objects arranged around themselves and their environment.

RQ1: What elements of spatial cognition can be leveraged in immersive environments to best aid users in information retrieval? This overarching research question is designed to address how information retrieval can utilize the findings of related research that has looked into how immersion affects memory, simple visual search, and path integration.

RQ2a: How do different spatial arrangements of information impact the ability of users to find information? The research I have looked at suggests that immersive technologies can assist with simple visual search. This question asks if those findings can apply to more complex text-based search tasks. Related is the question: **RQ2b: How do different spatial arrangements of information impact the ability of users to recall information?** Previous research suggests that recall is aided by IVEs, but I aim to observe how recall can be improved through spatially arranging information during the searching process.

RQ3a: What effect does using spatial arrangements of information have on users' perception of workload? If users feel they are working harder to search through spatial arrangements than they would in traditional computing without proportionate gains, they may be disinclined to use the spatial arrangements. A related question is **RQ3b: What effect does using spatial arrangements of information have on users' time spent on task?**

4 METHODOLOGY

There is a 2-phase approach to my research. The first phase is to conduct an exploratory user study. The second phase will be a set of user studies informed by the results of the exploratory study. The following section describes the methodologies and systems used for the exploratory study in progress. Many of the methods will be applicable to my future research work.

4.1 Experimental Design

I have developed an exploratory user study with a within-subjects, repeated measures design that compares three display conditions with different spatial arrangements of search results in an IVE using a VR HMD. The three conditions are: 1) LIST – an 8x1 2D list of search results that are common in search engines today (i.e. Google, Bing); 2) GRID – a 5x4 3D array of search results centered and angled around the user's forward view; and 3) ARC – a 2x10 3D arc of search results that surround the user in a 220 degree spatial arrangement (see Figure 2). The LIST display condition are designed to display 40 search results across 5 pages and to require as little head movement as possible. The GRID and ARC display conditions are the 3D spatial arrangements of search results and are designed to activate the vestibular and proprioceptive systems by requiring head and/or body movement to see all of the results and display the 40 search results across 2 pages.

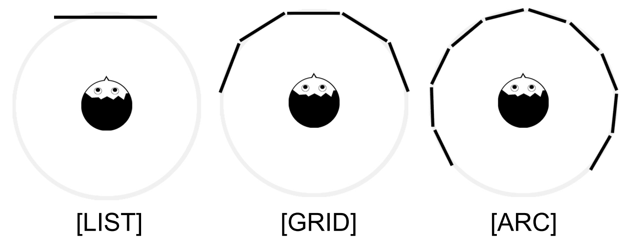

Figure 2: A top-down view of the display conditions.

Thirty-six participants will be asked to complete three tasks comprised of six search trials each. Each task will use one of the three display conditions for all six trials. All participants will be given the same 18 trials. Trials will be presented to the user as a set of search results and a description of a target search result to locate or to indicate that no relevant search result is available (e.g. From the given search results, find the result that will help you answer "What color is a giraffe's tongue." Find and select the relevant search result or indicate that no relevant result is available.). No querying will be done by the participants. Each trial will be populated by forty search results. Half the trials for each task will have exactly one relevant result in the search result set, which will be randomly assigned a position in the set. The other half will have no relevant results. The remaining results in the set will be non-relevant results on unrelated topics from Bing (e.g. a target result for "What is the height of the Great Sphinx of Giza?" will be surrounded by unrelated results about "baking a cake" or "how old is the telephone"). These trials are of equivalent complexity and have no preset time limit imposed.

Elements of the experimental design are influenced by previous studies using HMDs in a visual searching context [3, 18] and applied to the post-query, visual search component of the IIR process. The use of simple search tasks with pre-populated result sets with only one possible correct answer ensures that all participants are working towards the same goal and would allow for more comparable quantitative measures. The number of results in each set were a function of several factors: the desired amount of head movement, the size of display based on the number of results in view at a time, and the same total number between all conditions. The order of trials, the display conditions, and the presence of a target relevant result will be counter-balanced using balanced Latin squares. Participants will be seated during their interactions with the system. The participants' interactions with the virtual objects will be done with a handheld controller.

4.2 System Design

A system was built for the exploratory study and runs on the Oculus Quest VR HMD platform. The Unity game engine was used for development with the scripts written in Microsoft's C# language. Graphics were generated from Unity graphics primitives. The Oculus API allows the study application to track users head movements and head direction through the HMD. The application records all pertinent user-to-system interaction. Trial completion statistics like time-to-completion and correct search result target selected are also collected. All data is logged to an external database. This application was designed to be extendable with the knowledge that it could be used as a foundation for future studies.

4.3 Data Collection and Analysis

In the exploratory study, interface interaction data will be collected as outlined in the section above. After each set of six trials in a single display condition, users will be asked to fill out a questionnaire about that display condition. These post-task questionnaires ask questions on a 7-point Likert scale and are designed to collect responses for the following metrics on for each display condition: perceived workload, perceived difficulty in system use, confidence in answer selected, interface clarity, and self-reported feelings of motion sickness. The questions are derived from those on the NASA-TLX, SUS, and Simulator Sickness questionnaires [2, 8, 12]. There is also a questionnaire at the end of the session that asks participants to compare their experiences across the different display conditions and an exit interview that asks open-ended questions about their experiences in the IVEt. I will use a combination of quantitative and qualitative methods to analyze the data collected.

The questionnaire metrics are designed to get at RQ2a, RQ3a, and RQ3b.

- How mentally demanding was the task? **(RQ3a)**
- How physically demanding was the task? **(RQ3a)**
- How hard did you have to work to complete the task? **(RQ3a)**
- How difficult was it to determine when a correct result was not available? **(RQ2a)**
- Overall, I felt this task was easy. **(RQ2a)**
- I am satisfied with the amount of time it took to complete this task. **(RQ3b)**
- I thought the arrangement of the search results made this task easy to complete. **(RQ2a)**
- I felt confident in the answers I selected. **(RQ2a)**
- I felt generally uncomfortable while using this display condition. **(RQ3a)**
- I felt eyestrain while using this display condition. **(RQ3a)**
- I felt dizzy while using this display condition. **(RQ3a)**

For the quantitative analyses, I will use parametric (e.g., ANOVAs, regression) and non-parametric (e.g., Kruskal-Wallis) statistical tests to investigate the main effect of display conditions and the main effect of target presence. For the qualitative analysis, I will analyze participants' responses to the open-ended questionnaire and interview questions to understand participant's satisfaction or dissatisfaction with each display condition.

5 PROGRESS AND FUTURE WORK

I completed data collection for this study in late 2019 and am currently performing data analysis. My current plan for my dissertation work will involve a set of user studies to address the RQs not addressed by my exploratory study. The user studies will include: 1) For **RQ1**, incorporating the display-fixed and world-fixed spatial arrangements of information in addition to current, 2) For **RQ2b**, including non-textual information in search results, and 3) For **RQ1**, using an AR HMD to include the real-world environment and objects in the IIR process. As the system evolves, I am considering some of the following to add to the search system: a querying function with live search results, allowing users to access the landing pages of the search results, and incorporating more complex tasks.

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