Reexamining the cognitive utility of 3D visualizations using augmented reality holograms

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ABSTRACT

3D visualization has received considerable attention over the past few decades. Much extant research suggests 3D visualization is not beneficial except for a small number of specific scenarios. Studies suggest that drawbacks of 3D visualization are often due to presenting visualizations on a 2D display. Recent advances in augmented reality allow for the creation of holograms, which appear as 3D objects in the physical world. These advances offer new possibilities for displaying 3D visualizations in more realistic 3D forms. However, little research has examined these new possibilities. In this paper we discuss a work-in-progress project aimed at reexamining the cognitive utility of 3D visualizations when displayed as holograms in augmented reality. We describe a space-time cube prototype that is under development for the Microsoft HoloLens platform. We also outline plans for an exploratory study that will investigate types of knowledge and cognitive processes used while interacting with holograms compared to visualizations in traditional 2D displays.

Index Terms: H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous—

1 INTRODUCTION

3D visualization has received considerable interest since the early days of visualization research. While theoretically providing benefits by making use of an additional dimension, 3D visualizations have a series of drawbacks, such as those related to occlusion and depth perception. Studies suggest that 3D visualizations have advantages over 2D visualizations in specific situations and for certain types of tasks. For instance, 2D can be beneficial for tasks requiring detailed analysis and precise reasoning (e.g. [31, 32]), while 3D can be beneficial for tasks requiring overviews and more holistic reasoning [32] [37]. While studies have consistently shown mixed or negative results of 3D visualizations [12], many of the drawbacks are related to displaying 3D visualizations on 2D displays [18]. Multiple studies suggest that physical 3D representations do not share the same drawbacks as 3D digital representations, largely due to tangible and embodied aspects of interaction with physical objects [17, 19]. Historically, technological limitations have not easily allowed for digital projections of data into 3 dimensions. Display technologies—whether traditional monitors, interactive tabletops, projections, or otherwise—have primarily used 2D media for visual representation. Recent advances in augmented reality (AR) and head-mounted displays (e.g., Microsoft HoloLens), have enabled the display of data in more realistic 3D settings. For instance, when using the HoloLens, holograms can appear to users as regular 3D objects in their natural environment. Such advances offer opportunities to reexamine the cognitive utility of 3D visualizations, as advanced display formats, such as holograms, may not suffer from the same disadvantages as 2D displays.

Figure 1: Space-time cube hologram in an AR environment as seen through a HoloLens (L). Participant wearing the HoloLens (R).

In this paper, we discuss a work-in-progress project aimed at reexamining the cognitive utility of 3D visualizations when displayed as holograms in an AR setting. We have chosen the space-time cube as a testbed, due to its 3-dimensional nature—i.e., two spatial dimensions and an additional temporal dimension. We describe the development of our space-time cube prototype for the Microsoft HoloLens platform (see Figures 1 and 2). We also outline plans for an exploratory study that will investigate types of knowledge and cognitive processes used while interacting with holograms compared to 3D visualizations in traditional 2D displays.

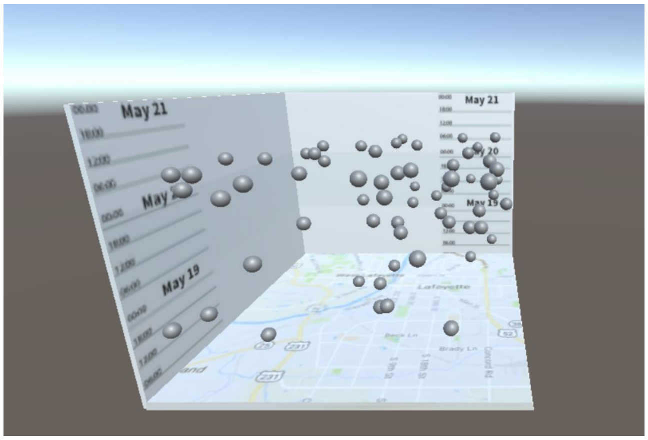

Figure 2: Space-time cube on a traditional 2D display.

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2 PREVIOUS WORK

3D visualization has been investigated in various disciplines and contexts, including information visualization [7], mathematical visualization [22], chemistry visualization [33], and others. Tradeoffs of 3D visualization have been debated and several issues have been identified [5, 27, 31]. Despite the disadvantages, research suggests that 3D visualization offers advantages as well, such as having an extra dimension for encoding data and being able to use different interaction techniques [5, 23].

One of the key advantages of 3D visualization is the ability to encode data in the third dimension. This advantage is best exemplified with spatio-temporal data. For example, while the x-axis and y-axis can be used to present geographical locations in 2D, the third dimension (z-axis) can be useful if additional variables such as time are added. Alternative encodings, such as size or color, can cause occlusion and other problems [14].

2.1 Display Considerations

Traditionally, 2D computer screens have been used to display visualizations. When data is inherently 3 dimensional, a flattened representation is projected onto a display medium. This practice can result in various problems, such as occlusion, distortion, and a loss of multi-dimensional information. Occlusion occurs when an object blocks another object from view, which is common when using 3D visualizations. Several techniques have been proposed [12] to minimize occlusion issues, as these are quite common in several examples of 2D visualizations as well, such as scatterplots and bubble plots. Shadows, grids, lines, minimaps, and color are commonly used to assist users spatial perception in digital content [11]. These techniques are helpful when dealing with simple datasets, but are not very effective when dealing with more complex datasets [24]. Although alternative means of displaying 3D visualizations have been devised—e.g., physical 3D prints and stereoscopic cave systems—there are tradeoffs inherent in them as well [17, 27].

2.2 Cognitive and Perceptual Considerations

We perceive objects in the world as being three dimensional (i.e., having length, width, and depth). However, the projected image of these objects on the retina is flat (2D), thus depth information is lost or distorted. As this is the case, monocular cues such as occlusion, relative size, and linear perspective are used to make assessments about 3D features. This effect is believed to happen as long as a 3D figure is flattened, as on a computer screen or on a printout [28].

The effects of perception have been studied within the AR community, specifically the perception of virtual objects within the real world [21, 29]. This is beneficial for data visualization, as users are able to use the spatial cues to encode data such as position, size, and motion [25, 26]. Some potential solutions for addressing perception problems, such as visual cues (active or passive), distance, location, and shape have been proposed [24, 36]. It is still unclear whether a computer-based implementation of 3D visualization would produce spatial memory advantages or disadvantages [10, 20].

Spatial Ability—In various sciences, such as chemistry and biology, certain concepts and structures that are inherently 3D (e.g. molecules and cells) are traditionally represented with 2D pictures and diagrams. This practice often leads to confusion, as students often form incorrect or incomplete mental models. 3D visualization has been argued to possibly help to from correct mental models and to improve incorrectly formed ones [8].

Spatial ability is of immense importance for the formation of mental models, and for the comprehension of 3D information in general [18,35]. Even though 3D visualization seems to be beneficial for forming correct mental models, research suggests that some students benefit more from working with 3D visualizations than others. For instance, Huk [15] revealed that students with high spatial ability stay within workable limits in terms of cognitive load when working with 3D visualizations. Students with low spatial ability, on the other hand, suffer from an unmanageable cognitive load. Further research needs to be conducted to ensure low spatial ability users also benefit from working with 3D visualizations.

2.3 Navigation and Interaction

Navigating in 3D space has been noted as a problem with 3D visualization. Most interfaces use a mouse and keyboard as means of specifying interactions, which are known to have disadvantages 3D contexts. For example, multiple clicks are often required for simple operations, which result in additional mental calculations for interpreting spatial relationships in a 3D environment. In one study, performing a mental rotation in a 2D interface was shown to be harder than performing one in a virtual reality (3D) setting [28].

Past AR research suggests three different methods for dealing with navigation problems: *Fixed in Space* [6], *Fixed on Device* [16], and *Head Coupled Perspective* [13]. Each of these methods has its advantages and disadvantages. *Fixed in Space* can create more room for interaction, while *Fixed on Device* will work best in a limited space, due to users not being forced to walk around to see the dataset. With *Head Coupled Perspective*, users have a better concept of depth and are able to explore and understand the dataset faster. These different advantages suggest that a combination of above techniques should be considered as a solution, based on the setting and circumstances of the 3D visualization.

3 REEXAMINING 3D VISUALIZATION

Due to the unique opportunities offered by AR holograms, we plan to reexamine the cognitive utility of 3D visualizations when displayed in hologram format. We are interested in the following research question: **What is the cognitive utility of holograms compared to traditional 2D displays for visualizing 3D data?**

3.1 Holograms

In this study, we propose to use the HoloLens—an AR, head-mounted, binocular stereoscopic display. There are several reasons for using the HoloLens. First, it allows digital objects to be superimposed in the real world, and users can easily interact with them. Second, the HoloLens allows users to feel immersed while still being aware of their surroundings. Third, binocular stereoscopic displays are known to improve users' ability of spatial judgment and 3D object recognition [1, 9]. When utilizing a head-mounted display, the interaction changes from basic mouse and keyboard to a more embodied experience requiring physical actions and movements.

3.2 Embodied Aspects

Research in the cognitive sciences has demonstrated the fundamentally embodied nature of cognitive activity. In various domains, advantages are consistently found as a result of having users physically manipulate objects or move within a space while performing cognitive activities [34]. We are intrigued at what implications the more embodied, physical nature of working with holograms (e.g., physically walking around them, having them co-located with other objects the physical environment, moving and manipulating them with one's arms and hands) may have for their cognitive utility. Studies have shown that navigating with a mouse can create high mental workload while working with 3D objects [30]. This effect is likely due to several different factors related to displaying 3D visualizations in a 2D display (e.g., occlusion) [34]. We are curious if this effect will change when using holograms.

4 PROPOSED STUDY

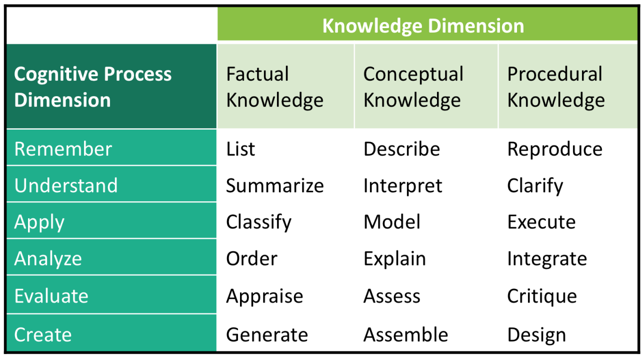
We plan to conduct a mixed-methods (i.e., combined qualitative and quantitative) exploratory study to help answer the aforementioned research question. Visualization evaluation typically relies on providing users with a series of tasks and assessing performance on them.

The tasks chosen in studies are often geared towards specific features of the data or context of use, and results may not be generalizable. Furthermore, they may not provide a robust picture of the cognitive utility of the phenomenon under investigation. To build a robust understanding of the cognitive utility of 3D visualizations displayed via holograms vs. traditional displays, we plan to examine levels of cognitive engagement and types of cognitive processes. We propose to use a revised version of Bloom's taxonomy [2], to help with the assessment of cognitive engagement and processes. Although the taxonomy comprises cognitive, affective, and sensory domains, we are interested for now in the cognitive domain only. The taxonomy is well-established and has been validated through numerous studies throughout the past half-century. Thus, we believe it can serve as a useful theoretical framework for assessing the cognitive utility of 3D visualizations.

4.1 Theoretical Framework

Bloom's taxonomy, originally proposed by Bloom and colleagues [4], aimed to ease the process of creating annual examinations by classifying learning objectives. It included six major categories: knowledge, comprehension, application, analysis, synthesis, and evaluation. The categories were arranged hierarchically, from simplest or most concrete (e.g. knowledge) to most complex or most abstract (e.g. evaluation). Furthermore, each category served as a pre-requisite of the next one, essentially forming a cumulative hierarchy. A revised version of the taxonomy [2], which underwent substantial changes but retained its hierarchical structure, is to be used in this study. The revised version can be partially seen in Figure 3, where it is divided into two main categories: the *knowledge* dimension and the *cognitive process* dimension.

Bloom's taxonomy provides a unique framework for assessing levels of cognitive engagement and types of cognitive processes. The cognitive process dimension functions as a continuum of increasing cognitive complexity, from *remember* to *create* (top to bottom in Figure3). The lower levels require lower-order thinking skills, while the higher levels require higher-order thinking skills. Educational researchers have identified specific cognitive processes that correspond to the different levels of cognitive complexity. For instance, the *remember* category contains cognitive processes related to recognizing and recalling information; the *apply* category contains those related to executing and implementing; and the *create* category contains those related to producing and planning. The knowledge dimension represents a range from concrete (factual) to abstract (conceptual and procedural) knowledge. The taxonomy contains another type of knowledge—metacognitive knowledge—but it is omitted in Figure 3, as we are not interested in assessing metacognitive processes at this stage of the research.



	Knowledge Dimension		
Cognitive Process Dimension	Factual Knowledge	Conceptual Knowledge	Procedural Knowledge
Remember	List	Describe	Reproduce
Understand	Summarize	Interpret	Clarify
Apply	Classify	Model	Execute
Analyze	Order	Explain	Integrate
Evaluate	Appraise	Assess	Critique
Create	Generate	Assemble	Design

Figure 3: Sample tasks that represent different cognitive process dimensions and knowledge dimensions, adopted from the revised version of Bloom's taxonomy [2].

4.2 Test Bed and Implementation

We plan to use a space-time cube as a testbed for our investigation, for two main reasons: (1) the data is inherently 3 dimensional, and (2) it is a well-established visualization technique that has already been investigated in various contexts (see [3]). Because a space-time cube comprises two spatial dimensions and one temporal dimension, it is a natural candidate for studying 3D visualization. Other visualization techniques—such as scatterplots and trees—can also be projected into 3 dimensions, but do not necessarily have natural spatial mappings, and may not be as beneficial in AR settings.

Two prototypes are currently under development—one for the HoloLens and one for a traditional desktop display. Both applications are being developed using the Unity 3D software. To avoid potential confounding variables, interaction possibilities in each will be limited—e.g., users will be able to only rotate, zoom, and select.

During the experiment, participants in different groups will work with a space-time cube visualization in their respective display types, and will be asked to complete specific tasks. At the end of the session, participants will be interviewed individually to determine their thoughts and opinions.

Control Group—Participants from the control group will work with 3D visualizations via traditional 2D displays (see Figure 2).

Experimental Group—Participants from the experimental group will work with 3D visualizations projected as holograms in an AR environment (see Figure 1).

4.3 Tasks

In an attempt to gain a robust picture of the cognitive utility of 3D visualizations, participants will be asked to perform 18 different tasks (6 cognitive process dimensions x 3 knowledge dimensions; see Figure 3). Using the taxonomy described previously will enable the assessment of types of cognitive processes and knowledge involved, rather than the assessment of only standard performance-based metrics (e.g., time and error). Due to the burden of conducting so many tasks, instead of a factorial design that asks each participant answer all 18 questions, we consider a block design to be more appropriate. Examples of tasks for the different types of knowledge and cognitive processes are listed below.

Factual knowledge—list the items of a certain category within the space-time cube; **summarize** the temporal trend of a certain process; **classify** the entities within the visualization based on a set of characteristics; **order** the items in the visualization based on their temporal and/or spatial sequence; **appraise** the visualization to determine any missing data points; **generate** a report that includes the behavior of a set of entities in the space-time cube over a period of time.

Conceptual knowledge—describe the characteristics of some entities within the space-time cube; **interpret** the meaning of point x being or above below point y; **model** the behavior of an entity over time; **explain** the patterns in a particular area of the visualization; **assess** the likelihood of x being a causal factor for y; **assemble** a set of resources needed to answer questions that cannot be answered clearly from the space-time cube.

Procedural knowledge—reproduce a portion of the space-time cube; **clarify** a set of instructions for interpreting the space-time cube; **execute** a series of steps needed to answer a specific question about the data; **integrate** steps needed to answer multiple questions about the data; **critique** another person's process of using the visualization to answer questions; **design** a new strategy for effectively answering questions or forming hypotheses with the space-time cube.

4.4 Discussion

The research plan outlined here is exploratory in nature. Although it would be possible to construct clear hypotheses for more traditional, quantitative assessments (e.g., based on speed and accuracy), what we are proposing here is inherently qualitative and takes a more holistic perspective on cognitive performance. Furthermore, as we are not aware of any prior work in visualization that uses Bloom's or a similar taxonomy for evaluation, there are no clear precedents on which to base strong predictions. Hence, we plan to conduct an exploratory study that can build background information about this type of assessment. Future work can build on these results to conduct studies with more definitive and generalizable outcomes.

5 SUMMARY AND FUTURE WORK

Decades of research has led to certain established knowledge about the benefits and tradeoffs of 3D visualization. However, most findings from research studies are limited in applicability to 3D visualizations that are projected onto 2D displays. Technological advances in AR have opened new opportunities for displaying data in more realistic 3D forms. For instance, holograms displayed by the Microsoft HoloLens appear to users as real objects in their physical environment. To develop a robust picture of the cognitive utility of 3D holograms, we plan to assess types of knowledge and cognitive processes involved in performing various tasks. We will use a space-time cube as the testbed, and the revised version of Bloom's taxonomy as a theoretical framework for our assessments.

The next step is to conduct a mixed-methods experiment with our space-time cube prototypes. We plan on further testing different 3D visualization techniques to develop a more comprehensive understanding of the value of holograms for 3D visualization. Subsequently, we plan to extend this work to collaborative settings, to understand the value of holograms within the physical environment for collaborative activities. Results of this research can inform the design of visualizations for various display technologies that are rapidly maturing.

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