Evaluation of Spatial Abilities through Tabletop AR

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ABSTRACT
Research has been done into improving the means by which we organise and manage information. The usefulness of 2D versus 3D interfaces and environments has also been debated and evaluated. Human spatial abilities can be used to store more information about particular objects including their position in space. Our hypothesis states that as 3D objects contain more information about themselves and their relative position in space than 2D objects, although users take longer to process this information, they should be more accurate when searching and retrieving 3D objects.

The evaluation study conducted compared spatial abilities between a 2D version of a memory game and an Augmented Reality (AR) version. Results showed that participants took significantly longer to complete the AR 3D version of the game than the 2D version, but did so with significantly fewer attempts i.e. they were more accurate. These results are specifically relevant for the design and development process of interfaces for AR applications.

Author Keywords
Augmented Reality, Spatial Ability, Evaluation, Tabletop AR.

ACM Classification Keywords
H5.2. User Interfaces: Evaluation/methodology, H.1.2 User/Machine Systems: Human factors.

INTRODUCTION
Augmented Reality (AR) is an emerging technology to support interaction with spatial information [2]. It permits the user to interact and visualise 3D virtual objects that can be, for example, positioned on a real table. But the design and development of AR applications remains difficult; this is due to a lack of theoretical models, interface development guidelines and an absence of more systematic evaluations and user-studies in this area of research. In this paper, we describe an approach to evaluate the effectiveness of using 3D objects within a tabletop Augmented Reality environment for managing and retrieving information. The evaluation emphasises the effects of spatial memory in retrieving positions of objects within a predefined structure. Information management and retrieval is used within a number of fields. In fact it is so prominent that it forms a part of most people’s working day.

Information exists in the form of files on a computer, web pages on the internet, books in a library, records, accounts and invoices, music, or recipes spread over many cookbooks. Designers of information management systems constantly strive to increase the effectiveness of their systems to not only categorise information adequately, but also enable users to retrieve information quickly and in the least number of attempts. Web design rules and heuristics have been formed to shorten both the amount of time (such as minimising the overall size of pages in kb) and the number of attempts the user has to make (such as the three-click rule) before finding the right information. Our research aims to take these two measures (time and number of attempts to complete the task) and evaluate what effect presenting information as 3D objects in an AR environment has on them.

For the evaluation two versions of a popular game called the *Game of Memory* were implemented. The first version contained pictures of objects (2D), whilst the second version was a tabletop AR environment containing virtual 3D versions of the same objects. An evaluation study was conducted and objective and subjective results were recorded and analysed.

RELATED WORK

Tabletop Augmented Reality

Augmented Reality is a means by which computer generated entities can be displayed within the real world, allowing users to interact with computers in a natural way; AR annotates the real world [1]. More information about AR and a survey of the field as a whole can be found in [2]. An updated version of the survey can be found in [3].

Unlike Virtual Reality (VR) where the user is immersed in the computer generated environment, AR allows the user full view and interaction with the real world, while still being able to see and interact with virtual objects. Until recently, most AR prototypes were developed to display virtual objects in the real world without much ability for user interaction.

In 1997, Ishii and Ullmer proposed the idea of tangible bits [4]. This was seen as an extension of Human Computer Interaction (HCI), whereby users could manipulate 'tangible bits' in the user's focus, which acted as interaction devices with the virtual objects. Using this system, any real surface could be turned into an active interface with the virtual world, seamless coupling could be achieved between both worlds (the real and the virtual), and ambient media (e.g. sound, light, airflow) could be used to provide cues for peripheral human perception. Since then, tangible user interfaces (TUI) have been developed. Tangible User Interfaces are real world objects that give physical form to digital representation [5]. These objects can be used to interact with and manipulate digital information in the virtual world. Examples of tangible user interfaces are given in [5]. *PingPongPlus* is an AR ping-pong game designed with an athletic TUI with various settings [6]. Markers and paddles can be used for interacting with virtual objects.

Furthermore, gestures with paddles can be used to simulate certain types of behaviour [7]. Another TUI, the magic cup, is a transparent cup that can be used to pick up, put, move, and delete objects [8]. In the real world, a lot of user interactions with objects occur over a tabletop environment. Collaborative meetings, design work, certain games, and many other tasks require fairly precise interaction with objects on a tabletop. Tabletop AR utilises tangible user interfaces to interact with objects. Work is currently being done into occlusion, using natural markers (such as the hands), and more accurate registration [9]. An example of a tabletop AR game can be found in [10].

Spatial Ability

Spatial ability is the ability of humans to perceive an object's position in 3D space. Spatial abilities differ for each individual. The part of working memory that is concerned with spatial ability and positioning is called spatial memory. Research has been done into using spatial memory capabilities to manage information. *Web Forager*[1] was an early attempt at using 3D objects to categorise web pages using the *Web Book* on the internet.

Data Mountain [11] was developed by the Microsoft Research Group to categorise Internet Explorer favourites in a 3D environment, making use of spatial memory for faster retrieval. *DocuWorld*, a 3D information management system uses the *Thought Wizard Metaphor* in a 3D environment to categorise and represent semantic structures to enable users to manipulate and retrieve documents more efficiently [12]. *Dynapad* provides visual access to personal libraries of PDF documents and photos, while using spatial abilities to categorise and organise information for faster retrieval [13]. Different evaluation studies and research has looked into the benefits of using 3D versus 2D environments [12, 14, 15].

Within AR, evaluation of spatial memory on human based performance found that spatial memory aided in memory and retrieval tasks [16]. In [17], an evaluation study confirmed that retrieval performance was improved when documents were represented by objects in a virtual environment, and furthermore when the spatial-semantic mapping was high. The influence of age on spatial ability, and thus the ability to navigate through a set of web pages was evaluated in [18]. In this evaluation it was found that as age increased, spatial abilities decreased, making web navigation, and thus the retrieval of information more difficult. Spatial memory was also linked to comprehension of information.

EVALUATION EXPERIMENT

Hypothesis

3D objects provide the user with a lot more information than 2D objects. This means that it should take the user longer to process this information when seeing the 3D object and relating it to a meaningful position in space. However, 3D objects also provide the user with more spatial cues, allowing the user to store in their memory more information relating to the object and its relative position in space. Therefore a user should be more accurate when retrieving a previously seen 3D object than its 2D counterpart. Relating this to our experiment, we expect that the time measures for the experimental version (AR 3D virtual objects) to be higher than the control version (2D pictures), but the number of attempts to be lower for the experimental version.

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[1] http://www.usabilityviews.com/uv008871.html

Setup

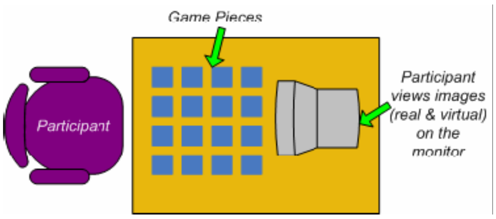

Figure 1. Plan view of the experimental setup.

Figure 1 shows the overall physical layout of the experiment. For both versions of the experiment, the participants sat in front of a table and were presented with a 4x4 matrix of game pieces (see also Figure 2). The subjects wore a hat with a webcam attached to it, which captured a live video feed of their field of vision. This was then sent to the application running on the workstation, and then rendered on the monitor.

Figure 2. Game pieces for the control group with 2D pictures.

There were 32 game pieces in total; 16 for each version of the experiment. For the control version, the game pieces were 2D pictures of objects, whilst for the experimental version the game pieces were markers to display the 3D virtual objects (Markers are a means of retrieving a spatial registration from a computer image in order to calculate the camera – object transformation). Each marker was unique, thereby removing any perceivable association between the marker and the virtual object. Printed markers and pictures by themselves as game pieces have disadvantages: they are easily damaged rendering especially the markers useless, and they are difficult to manipulate. For these reasons, the game pieces were made out of 20mm thick foam with the markers or pictures affixed to them.

The experimental version game pieces had 80mm markers affixed to one side (see Figure 3). This was to display the virtual objects. The control version game pieces had 2D images of similar objects used in the experimental version affixed to the game pieces (see Figure 2). All game pieces were approximately 95mm x 100mm.

Figure 3. Game pieces for the 3D AR version with the respective objects.

Software

Two versions (control and experimental) of an application were created to use in this experiment. These were both implemented using AR-Toolkit and run on the workstation. The primary purpose of the experimental version of the application was to display the virtual objects on the markers. Live video feed was captured using the webcam mounted to the hat on the user's head. This was then sent to the application to render both the virtual and real objects on to the monitor. The primary purpose of the control version of the application was to simply render the live video feed on to the monitor, so as to keep the user interaction consistent between both versions of the experiment. In both instances, users manipulated the game pieces by viewing them in the monitor, not viewing them directly.

EXPERIMENT

The experiments were conducted in a room specifically setup for this experiment in the Computer Science & Software Engineering building at the University of Canterbury. The experiment was run within groups (i.e. each participant did both the control and experimental versions). Half the participants were presented with the control version initially and the other half with the experimental version. In both versions, the subjects were asked to perform a task: to play the *Game of Memory*. The game intention is to uncover two identical set of cards from an array of cards with only two open at a time. The version used in the experiment used eight sets of twin cards.

Figure 4. User with the 2D control condition.

Participants

Twenty five (13 male and 12 female) voluntary participants took part in the experiment. Participants ranged in age from 20 to 40. Participants were approached by the authors and asked if they would like to participate in the experiment. They did not form any particular group of society (e.g. they were not all university students). When selecting participants, preference was given to people who had no prior experience of AR. An equal number of males and females were also sought after. If possible, people from different backgrounds (fields and ethnic backgrounds) were also selected. Subjects did not receive any remuneration for their participation.

Apparatus

Materials consisted of a workstation running an implementation of our application, 32 square pieces of foam (the game pieces), and a webcam mounted on a hat. Half the foam game pieces had markers fixed on one side, while the other half had the 2D pictures of the objects fixed on one side. Additional equipment such as webcams for recording the experiment, and time pieces for recording the time were also used. Consent forms and questionnaires were also printed for participants to fill in. The application consisted of two smaller programs: the experimental version and the control version. The experimental version was created using AR-Toolkit and displayed virtual objects on the markers mentioned above, rendering the augmented scene onto the monitor. The control version merely rendered the output of the webcam onto the monitor.

Method

The experiment was setup as shown in Figure 1. Each participant was presented with 16 (4x4 matrix) game pieces in both the control and experimental settings. The game pieces were initially placed face down. Each participant wore a hat with a webcam attached to it. This webcam was positioned almost at eye level, in between their eyes.

In the pre-experimental phase, the participants were given information about the experiment and asked to fill in a consent form.

Figure 5. User with the 3D Augmented Reality condition.

They were then presented with each one of the versions in turn. Before each version, instructions were read out. Users were asked to always look at the monitor while manipulating the game pieces. Prior to entering the experimental phase, they were given time to play with the game, familiarise themselves with the various objects, confirm that all equipment worked correctly (such as the positioning of the webcam, the lighting etc), and to ensure that they were both comfortable and within easy reach of the pieces.

The experimental phase consisted of the subjects playing the *Game of Memory* in both the experimental AR and the 2D control versions. The time taken to complete the game and the number of attempts were recorded. A video of the experiment was also recorded for further analysis. The post-experimental phase consisted of users filling in the questionnaire and a short informal interview.

Measurements

Objective and subjective measures were recorded for the experiment. Two objective measures were recorded for both versions of the experiment: the time taken to complete the task, and the number of attempts. After each experiment, the participant was asked to fill in a questionnaire recording their subjective measures of the experiment. Each question required an answer from a nine-point scale. These were then collated and analysed. Each experiment was also video taped. This was so that the objective measures could be confirmed if necessary, and to record any observations regarding the experiment, or comments made by the user during the experiment. These were also used quite extensively initially to modify the experiment design (see section "Lessons Learned").

RESULTS

When using a within-groups experimental design, there could be alternative explanations for the differences between the versions, even if the difference is significant. These explanations could be due to the research participants having matured or improved during the period, the learning curve produced by the experiments themselves, or other factors that have caused greater understanding of the task as the task has progressed. To avoid this effect in our experiment, we divided the participants into two groups

(Group 1 and Group 2). Group 1 did the control version first, while Group 2 did the experimental version first. The results from both groups were then compared to see if there was any statistically significant difference, thereby confirming the presence of other confounding factors. The results were divided into two broad categories: objective measures and subjective measures. The objective measures recorded were time to complete the task in seconds, and the number of attempts made. Subjective measures were divided into five categories based on the questions from the questionnaire; these being:

- Q1. ease of interface use
- Q2. ease of remembering objects,
- Q3. ease of distinguishing between the objects,
- Q4. how real the objects seemed, and
- Q5. the fun aspect of each interface.

Time Performance

		Control		AR Setting	
Group	**df**	**Mean**	**SD**	**Mean**	**SD**
1	**23**	**132**	**33.6**	**186.6**	**76.5**
2	**23**	**139.3**	**50.0**	**168.1**	**74.3**

Table 1. Mean and standard deviation of the time taken.

Table 1 shows the means and standard deviations for time taken to complete both groups in the control and experimental versions.

		Control		AR Setting	
Group	**df**	**Mean**	**SD**	**Mean**	**SD**
1	**23**	**24.9**	**5.2**	**19.1**	**5.0**
2	**23**	**23.2**	**3.1**	**13.5**	**5.9**

Table 2. The mean and standard deviation of the number of attempts to complete the task.

Table 2 shows the means and standard deviations for number of attempts for both groups in the control and experimental versions. T-tests were conducted between the Group 1 and Group 2 control means and between the Group 1 and Group 2 experimental means for both the time taken and number of attempts. There were no significant differences between the means of Group 1 and Group 2 for both the time taken and the number of attempts, confirming that no significant learning factors during the tasks affected the experiment.

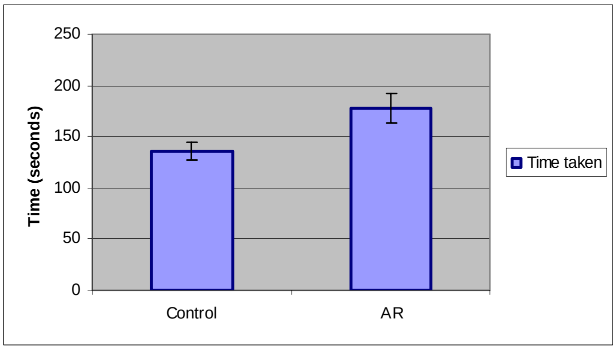

Figure 6. Means of the time taken between the control and the AR condition.

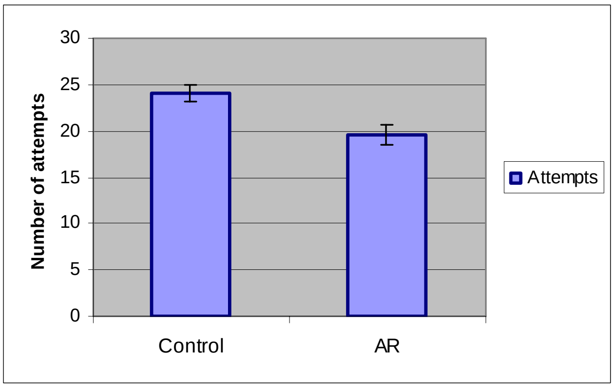

Figure 7. Means of the attempts between the control and the AR condition.

Objective Results

Time taken and Number of Attempts

Table 3 shows the mean and standard deviation for the time taken and the number of attempts in both the control and experimental versions. Figure 6 shows the means for the time taken in seconds to complete the task in the control and experimental versions. Figure 7 shows the means of number of attempts to complete the task in control and experimental versions. T-tests (two sample assuming equal variances) were conducted between the control and experimental versions for both the time taken and the number of attempts. The results for both the time taken and number of attempts were statistically significant at p<.01. For the time taken, $t(48) = 2.47$, p<.05 (one-tailed). For the number of attempts, $t(48)=3.27$, p<.01 (one-tailed).

	Control		AR Setting	
	Mean	**SD**	**Mean**	**SD**
Time	**135.5**	**41.5**	**177.7**	**74.5**
Attempts	**24.0**	**4.3**	**19.56**	**5.4**

Table 3. The mean and standard deviation for time taken and number of attempts in both the control and experimental versions.

Subjective Results

	Control		AR Setting	
	Mean	**SD**	**Mean**	**SD**
Q1	**7.0**	**1.1**	**7.1**	**1.4**
Q2	**7.0**	**1.4**	**6.8**	**1.6**
Q3	**7.0**	**1.5**	**7.4**	**1.4**
Q4	**5.8**	**1.8**	**7.2**	**1.6**
Q5	**6.4**	**1.9**	**8.0**	**1.2**

Table 4. The means and standard deviations of subjective measures.

Table 4 shows and the means and standard deviations of subjective measures collected from the questionnaire for both the control and experimental versions. T-tests (two sample assuming equal variances) were carried out on each category (Q1 to Q5) of the subjective measures. For the perceived ease of interface use (Q1), ease of remembering objects (Q2), and ease of distinguishing objects (Q3) there were no significant differences reported between the two interfaces. Users reported that there was significant difference between how real the 3D virtual objects looked as opposed to their 2D counterparts; the 3D objects in the AR environment looked more real: $t(48)=2.79$, $p<.01$ (one–tailed). They also reported that the AR interface was more fun to use than the 2D control version. $t(48) = 3.5$, $p<.01$ (one–tailed).

DISCUSSION

From the objective measures results, there was a significant difference between the control version (using the 2D interface) and the experimental version (using the AR 3D interface) for both the objective measures (time taken and number of attempts). The time taken to complete the task in the 3D AR interface was significantly higher than the time taken for participants to complete the task in the 2D interface. This supports the first part of our hypothesis. 3D AR objects contain a great deal more information than their 2D counterparts, requiring more processing, thereby increasing the time required to complete each task. The number of attempts required to complete the task was significantly lower in the 3D AR interface than in the 2D interface. This supports the second part of our hypothesis. 3D objects contain more information not only about themselves but also about their relative position in space than their 2D counterparts. This spatial information makes use of the brain's spatial memory ability by storing a greater amount of information about the object's position in space. This enables higher accuracy during retrieval of the objects. The subjective results showed that the participants found both the interfaces equally easy to use (Q1). They also did not find remembering the objects easier in either of the versions (Q2). This could be because although they were significantly faster in the control version, they took significantly less attempts to complete the experimental version, thereby giving an overall feeling that both were similar in remembering. Users felt that objects in both interfaces were equally distinguishable (Q3). However, there was a significant difference in how real the objects looked. Participants felt that the 3D objects used in the experimental version were significantly more real-looking than the 2D objects in the control version. They also rated the AR experimental version significantly more fun to use than the 2D control version. Users were able to comment in both the questionnaire and the post-experiment interview. Most users commented on the fun aspect of the AR interface. Although the differences in Q3 were not significant, most users commented on the ease of picking out the 3D objects. Few users commented on the difficulty caused by trying to map between the view area and the object manipulation area, but these were equally difficult in both the versions. Some users felt they did worse in the experimental version of the task, however on analysis of their individual results it was found that contrary to their belief, they generally did consistently better in the experimental version. This could be due to the higher cognitive load required when processing the 3D objects. When viewing the video of the experiments, it was observed that users interacted easily and naturally with both interfaces. Users also treated the virtual objects as real objects; they moved around them rather than through them.

Lessons Learned

A number of lessons were learned during all the phases of the project. Five pilot experiments were conducted to redesign parts of the experiment and the experimental setting. The results for these pilot experiments were discarded.

Difference between View area and Objects

For this experiment, we opted to have the users view the objects on the monitor. While watching the videos of the first few pilot experiments, we noticed that the mapping problem introduced increased in two cases: first, as the distance between the view area and manipulation area increased, and second, as the angle subtended between the view area, the user's eyes, and manipulation area increased (see Figure 8 left). To minimise this problem, the distance between the view area and object manipulation area was minimised. The angle was also reduced by reducing the distance between the game pieces and the application window on the monitor. The distance and angle were then kept constant for all experiments.

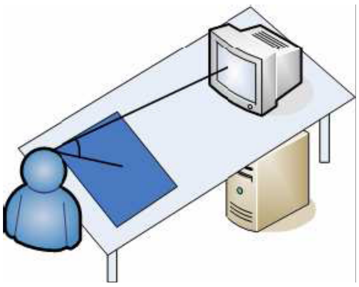

Figure 8. (Left) The greater the angle subtended between the object manipulation area, the user, and the view area, the greater the mapping problem. (Right) The webcam mounted on the cap to capture the user's view

Eye Displacement

In the initial design, the webcam capturing the subject's view was mounted on a fixed stand next to the user. This was done so that the camera could be fixed in a known position giving better rendering of the virtual objects. However, after the first few pilot experiments, it was clear that the eye displacement was causing mapping problems for users, making interaction unnatural and laboured. The user was not able to move their head to view objects just out of view; a very natural way of interacting. For this reason, a webcam was mounted on a hat, minimising the eye displacement, whilst enabling the user to move their head freely to view objects (see Figure 8 right).

Keeping all Variables Constant

The initial design of the experiment had users manipulating the experimental version game pieces directly while viewing them on the monitor, but manipulating and viewing the 2D version game pieces directly. Although this seemed like it was meeting the requirements of the experiment, we soon realised that this was not keeping all other variables constant between the two versions. The experimental version introduced a mapping problem (view and manipulation areas are different) which was not kept constant in both versions. To avoid this, we asked the users to view both the control and experimental game pieces on the monitor while completing the tasks.

The 'wow' factor

The initial design of the experiment saw the users go directly from instruction into the set task without any time to see the objects (3D virtual or 2D pictures). When seeing the 3D virtual objects augmented on to real surfaces for the first time, users forgot their tasks temporarily as they were captured by the novelty of the AR interface. This affected times drastically giving incorrect and biased measures. For this reason the design was altered allowing the users time (2 minutes) to play and familiarise themselves with the AR objects. Although this did reduce the bias greatly, we are not certain that it has totally eliminated it.

CONCLUSION

This project evaluated the effectiveness of using 3D objects for searching and managing information in a tabletop Augmented Reality environment. Research has previously looked at the benefits of using computer-based 3D versus 2D objects and environments for managing information. This paper combines the work done in both Tabletop Tangible User Interfaces (TUI) AR and spatial memory to evaluate the hypothesis described earlier on. Tabletop AR using tangible user interfaces gives the flexibility of using virtual objects in the real world environment. Users are able to freely and naturally interact with virtual objects in the same manner as they would with real objects. 3D objects also allow the user to gain more information about the object than their 2D counterparts. Human beings also have the ability to remember the positions of objects in space using their spatial abilities. The positions of objects within space are retained in their spatial memory. Research has shown this ability to aid in managing and retrieving information, and navigation tasks (such as navigating through web pages). A within-groups experiment was conducted at the University of Canterbury with 25 participants to evaluate the hypothesis. In the control (2D pictures) and experimental version (AR environment with virtual 3D objects), users were required to complete a task in the shortest possible time with the least number of attempts. The task was to play the game of memory. The objective results gathered supported the hypothesis. Users completed the control task in a significantly shorter amount of time. They also completed the experimental task with significantly less number of attempts. Both results were significant at $p<.01$. Subjective results showed that users felt the experimental interface was significantly more fun to use, and the objects in the 3D environment were more realistic. They also showed that both interfaces were as easy to use as each other. This research has implications in any field that requires the management and retrieval of information. It could change the way we think about designing our information management systems, and the technologies that might be best suited for this purpose. It could also add to what we know about how the brain processes and manages information.

FUTURE DIRECTIONS

There are a lot of aspects proposed for further work in this field. Manipulating different independent variables in similar experiments such as the one performed in this paper could give interesting and useful results. For instance, there has been research done to investigate age differences in spatial abilities and its effect on web navigation [18]. Similar studies using the experimentation techniques described in this paper could be done to investigate the effects of age, gender, and individual spatial abilities on the management and retrieval of 2D and Tabletop AR-based 3D information. In the experiment described in this paper, the user viewed their object manipulation area on the monitor. This caused mapping problems, as the view area and object manipulation area were not the same (see section 8.1). Using a head mounted display could ratify this problem. In the task described (playing the game of memory), users were required to retrieve objects from a predefined structure. The position of each object did not have any meaning or relevance to the user. This could have placed a higher cognitive load on the user as they tried to understand and comply with this predefined structure. In most information management systems, the user would have control over the semantic structure of the information. It would be interesting to do an experiment comparing the interfaces where the users placed information in user-specified positions (such as when saving files on a computer), and then retrieved them at a later time. As an extension, an evaluation study could be done on a real world application using both a current 2D application and an AR 3D implementation. The creators of *DocuWorld* have proposed an extension to their 3D information management project to add immersive content [12]. Extending applications such as *DocuWorld* or *Data Mountain* [11] to contain 3D AR content and evaluating the benefits of the AR version versus the computer-based 3D version, or a 2D information management system could yield interesting results, potentially leading to better designs for a wide range of information management and retrieval systems.

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