Spatial Memory in Virtual Reality and Desktop Interfaces

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ABSTRACT
Spatial memory has been proven to be significantly affected by the level of immersion a user experiences in an interface. The efficiency of using an interface can be improved greatly by improving spatial memory. In this study we offer a direct comparison of spatial memory between VR and desktop interfaces. Unlike past studies, this paper finds no significant difference between VR and desktop interfaces with respect to spatial memory, with a p-value of 0.38. There are a number of factors that could have influenced this result, but it is unclear exactly what the difference between this study and previous research is. Further work into the area should be done in order to determine what specific factors affects spatial memory in VR and desktop interfaces.

INTRODUCTION
Spatial memory is a crucial tool in the way humans interact with our environment. It allows us to recall the position of objects around us, and plan a route in order to reach them, formally defined as the "ability to recognize and understand spatial relationships (both in 2D and 3D)" [13]. The ease with which an environment supports forming spatial memory naturally increases a user's efficiency. For instance, most computer users will have a standard keyboard layout more or less memorized, which allows much faster typing than if they were to visually search and locate each key before pressing.

In order to maximise efficiency of interface usage, then, the ease with which spatial memory is formed should be optimised. While the majority of modern interfaces are present on a two dimensional (2D) screen, novel interface environments such as virtual reality (VR) are also increasing in popularity. The higher degree of immersion that VR offers has been shown to improve episodic memory [11] (memory associated with specific events or times), as well as being suggested to improve spatial memory formed during actively exploring environments [3].

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We are interested in the effect using a virtual reality system on spatial memory has, compared to the effect of using a traditional desktop display.

The next section describes related work, followed by a description of the testing environments and experimental procedures used. Results, conclusion and discussion are then presented.

RELATED WORK
There are a few areas of related work relevant to this investigation. First, we consider the spatial memory benefits of two-dimensional and three-dimensional interfaces as they appear on a traditional flat screen. Second, we consider the advantages and disadvantages previously found with user interaction in virtual reality. And lastly, we look at the specific effect the degree of immersion has been shown to have on spatial memory.

2D vs 3D: Spatial Memory
Early research into the difference in spatial memory for 2D and 3D interfaces indicated better memory recall in 3D [13] [14]. But further inspection into the difference between 2D and 3D interfaces with respect to spatial memory showed no effect with the introduction of 3D[5]. A later paper showed that because the 3D interface appeared more cluttered, it was more confusing for the users, who actually performed worse in this condition[6]. So the exact effect on spatial memory of increasing dimensions in an interface seems likely to be insignificant.

Virtual Reality, Layout, and Interaction
In a study by Brooks, actively participating in a scene was shown to improve the spatial memory of a location's layout, but not of specific objects [2]. If the objects in question are associated with a specific location in a detailed virtual environment (see Figure 2), they are able to be recalled with a superior ability in VR compared to a traditional desktop display [9] [12]. This is known as the method of loci (MOL) or a memory palace, a spatial mnemonic to help remember information.

An improved sense of presence was also theorised to improve performance of recall [4]. VR, which offers a greater sense of presence than desktop, could therefore also be theorised to improve recall. A study in memory elicitation in VR showed that more information about tasks was recalled by users in VR compared to a desktop environment in a virtual airport[7]. These objects were associated with location, in a similar way to the study involving the method of loci.

Figure 1. Memory object layout and environment from Krokos et al [9].

Immersion and Spatial Memory

A specific study on the effect of the degree of immersion on the user's spatial memory was conducted by Johnson [8]. They found that a higher degree of immersion - that is, a VR environment - caused a significant improvement in spatial memory recall. This would suggest that spatial memory is significantly easier to form in VR. However, these results may not be generalisable. Spatial memory is formed and stored differently in large-scale and small-scale environments [10]. Johnson's work focussed on the active exploration of a large-scale environment, and asked users to recall their path through a city street scene.

Note that here, large-scale environments and interfaces are defined to be those that are on such a scale that the user has to change their position (by walking, teleporting or similar) significantly to view all the objects or areas of interest. The key feature here is that the user perceives themselves as travelling through different parts of the environment. This means the spatial memory formed is likely to be based more on the route taken than the positions of the objects with respect to the user. A small-scale environment, on the other hand, allows the user to view all the objects of interest without significant movement required.

User interfaces commonly use small-scale environments with small-scale objects (eg. buttons) . These are points that would be useful to store in spatial memory. It would be useful, then, to specifically explore small-scale spatial memory in VR and desktop environments.

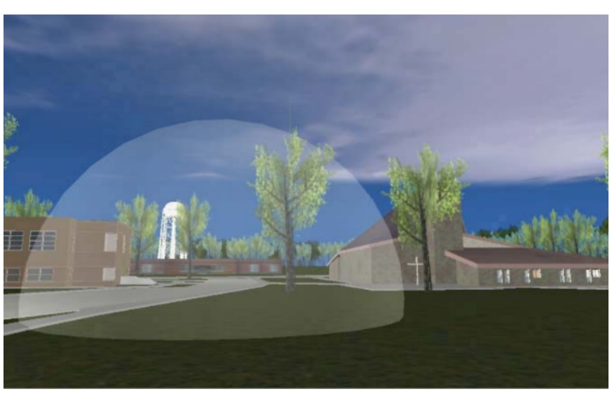

Figure 2. Memory object layout and environment from Johnson [8].

EXPERIMENTAL METHOD

The following methodology is presented to answer the research question of this paper using quantitative techniques. The testing environment, experimental design, and evaluation methodology are outlined.

Experimental Design

This study was run on human subjects with a quantitative research focus. Each subject was asked to participate in both experimental conditions (VR and desktop). The tests took around five minutes per participant.

Participants were randomly assigned to complete either the desktop or virtual reality testing condition first. This was to control the learning effects that could occur as the users became familiar with the environment and testing procedures.

The participants were put through a background questionnaire (to determine demographics factors such as sex), after which they were given written instructions on the experimental procedure. They were then put into the virtual environment, given a brief period of familiarisation time, and then a training period ensued.

During the training period (in both the VR and desktop display) the user would be presented with a stimulus object (Figure 5). They would then find the identical object located in the auditorium in front of them. When the user clicked on this object, a new stimulus object would be presented. Between clicking on the objects located in the auditorium, the user had to click on the stimulus object in front of them. This allowed a more controlled time for locating each object, and ensured that the time was more consistent, rather than moving the cursor directly from auditorium object to auditorium object. Each testing condition would have five stimulus objects associated with it, which were repeated three times each, and presented to the user in a random order. The emoji and letter positions were randomised for each trial.

After the training period, a short break period was set, moving to the testing period when the user was ready (no longer than twenty seconds). The user then went through the testing period, which was the same as the training period, and consisted of the same stimuli but with a newly randomised order. During testing of the experiment, making the panels blank for the testing period was considered, but enough of a difference in timing between the training and testing periods was observed that it wasn't necessary. Keeping the panels visible was considered to have a higher ecological viability for commonly used interfaces.

After the first condition was completed, the second condition would then be run in a similar way with training and testing phases. The symbols were completely different (emojis instead of ascii symbols) in the second condition to avoid interference with the user's memory of the first condition's symbol layout. Letters and emojis were randomized between the two conditions, to ensure that any effect the different symbols had on spatial memory would be averaged between participants.

The software measured and reported the time at the change between each phase (training, testing conditions, etc), as well as the time taken to find each stimulus object in both the training and testing phases. If the user clicked on the incorrect memory object, the distance between that and the correct memory object was recorded.

After the experiment, a Likert scale questionnaire was given to participants to determine which environment they had a better experience in, and which they felt was more efficient to use. Each statement was rated by the participants out of strongly disagree, disagree, neutral, agree, and strongly agree. The statements were:

1. I enjoyed using the desktop display.
2. I enjoyed using the virtual reality headset.
3. I enjoyed the desktop display more than the virtual reality display.
4. I was efficient in the desktop display.
5. I was efficient in the virtual reality headset.
6. I was more efficient in the desktop display than the virtual reality display.

Testing Environment

Two testing conditions were created to support the experiment: a traditional 2D desktop display (Figure 3), and a display in virtual reality (Figure 4). Both displayed the same 3D testing environment, which consisted of 55 panel objects displayed in a gridlike auditorium layout. They either displayed ascii symbols or emoji.

Navigation and Cursor

Navigation in the desktop display was implemented by the view following the movement of the cursor, modelled on a standard first-person gaming view. The centre of the screen was treated as the cursor, and as the 'real' cursor was invisible during the experiment, the user would believe the centre of the screen was the cursor. The experiment was run in fullscreen on the desktop display, to avoid any external factors interfering with the usage of the interface, and to avoid the cursor clicking on a different application and exiting the experiment.
Navigation in the virtual reality display was implemented by standard head tracking. The cursor position in virtual reality was also kept in the centre of the screen, meaning the participant had to physically move their VR headset to point at the appropriate object. In both VR and desktop conditions, a left-button mouse click was used to select an object.

Participants and Apparatus

17 volunteer participants (10 female, 7 male) aged 20 - 28 were recruited to participate in the experiment. 7 were regular gamers, and none were regular gamers in virtual reality.

The experiment was performed on a Windows 10 desktop machine, using a 13" monitor at a 1920x1080 resolution, running at a 60Hz refresh rate, and a Windows Mixed Reality headset with 1440x1440 resolution per eye and a 90Hz refresh rate. A

Figure 3. Testing environment using emojis as stimuli, as viewed in the desktop condition.

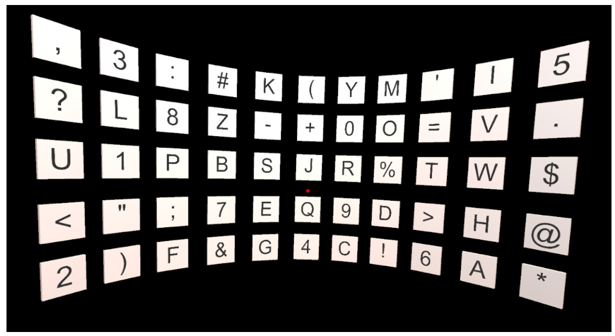

Figure 4. Testing environment using letters as stimuli, as viewed in the VR condition.

standard keyboard and mouse were used for interaction with the system. [1]

Data Analysis

In order to determine if there was a significant difference between the 2D desktop and virtual reality displays, a null hypothesis was formed:

H1: There is no significant difference between a desktop display and a virtual reality display with respect to spatial memory.

The independent variables included:

- The method of display (including the way the user navigates using that display),
- Sex of participant;
- Whether the participant is a regular gamer or not;
- Whether the memory objects displayed emojis or letters.

The dependent variables included:

- Time to click on a memory object;
- Performance increase, that is, the percentage decrease in time from the training period to the testing period;
- Whether or not the memory object matched the stimulus object;

[1]Due to the Covid-19 pandemic restrictions, real data was unable to be obtained, so the author ran the experiment 17 times to emulate the data that would be generated by real participants.

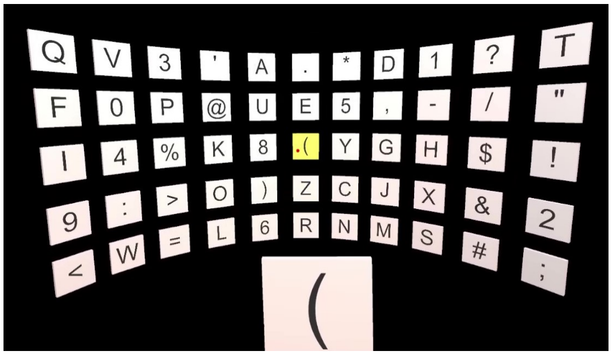

Figure 5. An example of a stimulus object, with the user's cursor hovering over the correct memory object in the grid in front of them.

- If the memory object did not match the stimulus object, the distance from the correct memory object to the one clicked on.

RESULTS

The average time to locate a panel during the training time and the testing time was 1.43s (σ 0.416) and 1.04s (σ 0.281) respectively, the decrease indicating that the effect of spatial memory was present in the experiment. In all except one case, the users' time to locate a memory object decreased from the training period to the testing period.

The number of incorrect clicks was insignificant - the most any one participant had was two. Therefore, no significant analysis could be done on the distance between the incorrectly clicked object and the object the participant was aiming for.

Overall

There was an overall decrease in the time to locate each stimulus object from the training condition to the testing condition (Figure 6). The average percentage decrease in time was 22.2% (σ 16.86) for the desktop condition, and 27.05% (σ 20.93) for the virtual reality condition. This was not a significant difference ($F_{1,16} = 0.8269, p = 0.3767$). Thus we fail to reject the null hypothesis, and find no significant difference between spatial memory for VR and desktop interfaces.

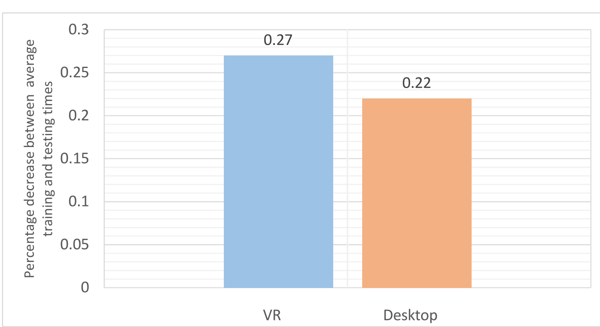

Figure 6. VR vs. desktop average percentage decrease between training and testing times.

Gamers vs. Non-Gamers

Participants were self-identified as either regular gamers (playing games at least once a week) or non-gamers. Figure 7 shows that there was little difference between gamers' and non-gamers' performance increase in the VR and desktop conditions. The average percentage decrease in time between training and testing conditions was 0.2640 (σ 15.04) for gamers and 0.2731 (σ 20.28) for non-gamers.

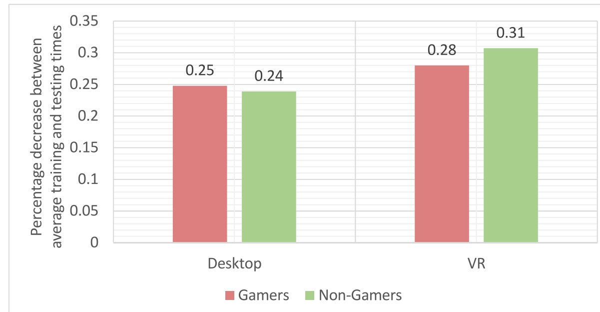

Figure 7. Percentage decrease in time for gamers and non-gamers, VR and desktop conditions.

Male vs. Female

Participants were self-identified as male or female. An option to decline the question was offered, but no participants opted out. The average percentage decrease in time between training and testing was 0.3065 (σ 23.67) for males and 0.2446 (σ 13.76) for females. Figure 8 also shows that males overall had a higher increase in performance, but there was no obvious difference in the differences between VR and desktop conditions.

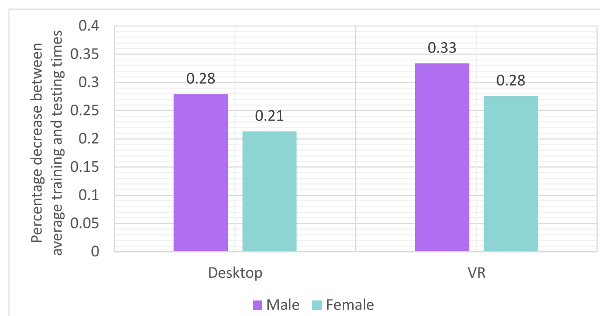

Figure 8. Percentage decrease in time for males and females, VR and desktop conditions.

Emojis vs. Letters

Two different symbol sets were used for the memory objects. Figure 9 shows a difference between the performance increase for letters and emojis specifically in the desktop condition, with a mean of 17.79 (σ 13.88) for emojis and 0.3281 (σ 14.27) for letters. However, no significant difference between letters and emojis in performance increase was found ($F_{1,16} = 0.9355, p = 0.3478$).

Likert Questions

The Likert scale questions generally indicated that:

- The users enjoyed the VR interface and felt neutrally about the desktop interface.
- The users felt they were efficient both in VR and desktop, but generally more efficient in VR.

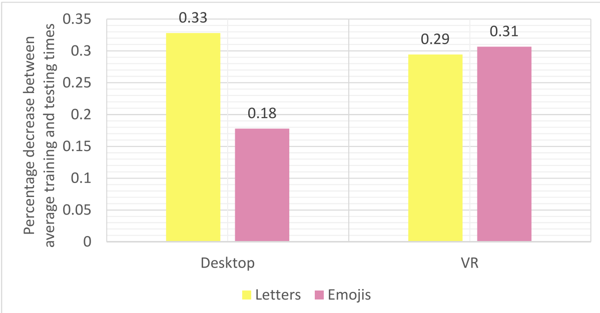

Figure 9. Percentage decrease in time for participants using letters and emojis, VR and desktop conditions.

These results were unsurprising, as the majority of the users didn't have any experience with VR, and getting to use it was an exciting novelty. The efficiency was correctly perceived - the average overall time in VR (1.19s, σ 0.486) was lower than desktop (1.28s, σ 0.294) throughout both conditions.

While no Likert questions were asked about emojis and letters, it is worth noting some users commented that they much preferred the emojis, and thought they performed better with them, despite the opposite being true (Figure 9).

DISCUSSION

No significant difference was found between the virtual reality and desktop conditions for spatial memory. This is an interesting result, considering that past research has typically found a significant improvement from desktop to VR with spatial memory [8] [9]. This could be for a number of different reasons, some of which will be discussed below.

This environment is defined as being a small-scale environment, where objects are all viewable from one position, and location is therefore remembered from one position. While a small-scale environment was used in Krokos et al.'s study [9], this was associated with the memory of loci (mind palace) technique. Our results imply that without the mind palace technique, there is no significant increase in spatial memory from desktop to VR. It would be interesting to determine if it is only the memory of loci technique (that is, associating each object with a specific location in a detailed environment) that causes the significant difference in performance, or if there is another factor that affects spatial memory - for instance, density of objects, number of objects, or method of memorisation. These were all different in Krokos et al.'s study.

Five stimuli objects were used in each condition. This is well within the number of short term working memory objects (7 ± 2 [1]) available for the average human. It may be that this was too easy to remember. Some interesting comments made by participants along the lines of "this was easier than expected" suggest that the five object locations were easy to hold in memory. It would be interesting to increase the number of stimuli objects past the limit of short term memory. This would mean participants would be almost certain to forget some of the object locations, which could offer a greater insight into any difference in spatial memory between desktop and VR conditions.

Limitations

A number of potential limitations have been identified in this study. The symbol sets had an effect (not statistically significant) on spatial memory. Using emojis made a larger difference between the VR and desktop conditions than letters did - in fact, spatial memory was (very marginally) better in desktop than VR using letters as symbols. The exact cause of this is unknown. Completely different symbol sets were required for this within-subjects study to avoid any interference in spatial memory between the conditions. It would be interesting to run a between-subjects study and use the same symbol set for each condition, to see if the same discrepancy between symbol sets prevails.

A decision was made to keep the objects in the grid visible during the testing phase for a higher ecological viability (interface buttons are never going to disappear). However, this may have reduced any difference between the desktop and VR conditions. For every participant, the number of incorrect clicks was no more than two out of the thirty clicks they had to make. Where spatial memory was not used, and the user forgot the location of the object in question, they could fall back on visual search to find the object. This means that the time was not only reliant on spatial memory, and the faster visual search times could have muddied the times that were reliant on spatial memory. It would be interesting to run a study that would make the objects blank during the testing phase, and for incorrect clicks, to analyse the distance between an incorrect object and the correct object.

CONCLUSIONS

Spatial memory has been proven to be significantly affected by the level of immersion a user experiences in an interface by several prior studies. This paper offers a direct comparison of spatial memory between VR and desktop, which has not been carried out before without using either a large-scale interface or the memory of loci method.

Unlike past studies, this paper finds no significant difference between VR and desktop interfaces with respect to spatial memory. There are a number of factors that could have influenced this result, but it is unclear exactly what the difference between this study and previous research is. Further work into the area can be done to determine exactly what affects spatial memory in VR and desktop interfaces.

FUTURE WORK

As previously discussed, there are a number of interesting areas open for continued exploration given the results of this study. The exact effects of several factors, as listed, have not been explicitly tested within this experimental design:

- Symbol sets (letters and emojis),
- Number of stimuli,
- Density of objects in grid,
- Method of memorisation, and
- Method of testing,

In particular, it would be valuable to narrow down the differences between this work and others which have found a significant effect on spatial memory between VR and desktop, to offer insight onto what specific factors influence spatial memory in VR and desktop conditions.

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