The effect of spatial design on user memory performance using the Method of Loci in VR

1st

***Abstract*—Based on the Method of Loci, the following experiment compares the effect of two different virtual environments on participants' memory performance. The primary task consists of remembering a sequence of random playing cards. Each virtual environment is based on a different architectural style with a different layout. One is inspired by a Palladian style architecture, and the other by a Modern curved architecture.**

***Index Terms*—virtual reality, architecture, memory, performance**

I. Introduction

Studies in psychology have already demonstrated that human long-term memory capacity is essentially unbounded [1]. How can we tap into this potential instead of increasingly rely on external devices such as smartphones, memory cards or the cloud to store our memories? The ancient Greeks had an answer for that. Before even they were able to write, they develop a technique to remember vast amount of information from memory. the Method of Loci (MoL) — aka memory palace, or mind palace [2]. By practising the MoL, one can quickly visualise in the mind's eye the latest public building they have visited, and organise a journey along which it is possible to attach information to be remembered.

From an architect's standpoint however, many questions start to arise. How would a building with its specific spatial design support the memorisation of a set of given information? How could the benefit of using one internal space over another be evaluated? Are there particular architectural elements necessary to facilitate such a process? Virtual Reality (VR) presents an opportunity to set up an experiment that would lead to potential avenues for finding answers to these questions.

Therefore, the main research question we formulate is as follows: which architectural properties can enhance humans' memory performance when using the MoL in VR? To help us answer this question, we have set to answer the following four sub-goals:

- G1: How to operationalize the MoL in VR.
- G2: Identify the cognitive principles behind the MoL and apply them in VR
- G3 Test that the MoL in VR can improve memory performance.
- G4: Evaluate the effect of different architectural properties on memory performance using VR.

A. A brief history of the Method of Loci

The Art of Memory (AoM) is a collection of mnemonic techniques, one of which is called the MoL [2]. It was the main method utilised for remembering information from the classical period of Simonides of Ceos in Ancient Greece to the renaissance era of hermeticism with Giordano Bruno. These techniques were almost universally practised by the thinkers of the ancient world, who believed that mnemonic training was essential to the cultivation of creativity.

Creativity was an act of synthesis that could only occur within the mind of a trained mnemonist. Appropriately, in Greek mythology, Mnemosyne, the goddess of memory, was the mother of the Muses. It was common for orators to memorise their speeches, or any other items, by imagining a journey (perhaps from their doorstep to the fora) with a sequence of places (loci) and mentally tracing their steps to recall each article or paragraph associated in each location. These techniques can be synthesised with the three pillars of memory: Imagination, Association and Location [3]. Imagination and Association give memory. Location gives the sequence.

B. Related Work

Following these events, the use of mnemonics based methods such as the MoL was, not surprisingly, neglected by the scientific community. Apart from the historical facts outlined above, demonstrating the efficacy of the MoL was challenging, given that participants rely on their mental imagery to implement the memory palace. One of the main difficulties one faces are the individual differences in mental imagery ability [4]. Other differences are the size and uniqueness of each environment, the amount of time spent in the environment, and the emotional associations one has with the space; many variables that are difficult to quantify.

Furthermore, people's use of effective mnemonic strategies is generally low [5]. Despite the endorsement of mnemonic techniques by universities, undergraduates who are exposed to mnemonic strategies as part of their academic curriculum often do not implement them in their daily practice [6]. One of the main contributing factors to this apparent mental barrier is the need for long training periods before the technique becomes effective [7].

As such, an investigation can benefit from an experimental approach that provides participants with standardised environments such as familiar nearby locations or virtual environments which participants can be exposed to in a more controlled manner [5]. In a pivotal study by [8], the research subjects received instructions to use either a virtual environment for the MoL (on a desktop monitor), or a traditional MoL (using their imagination), to remember 10 lists of unrelated words. Firstly, it is noteworthy that the subjects using the traditional MoL had trouble completing, which relates to the mental barrier mentioned above; secondly, the virtual environment was as effective in supporting memory as the traditional MoL. This was a first step in demonstrating the potential of using VR as a new methodology to study the MoL. A more advanced study that has converted the MoL into VR by [9] shows encouraging results where the experimental group remembers 28% more objects than the control group. But this study ended being based on a desktop version because the deployed VR version, using the Oculus DK1 (3DOF), was causing motion sickness. Before going into the details of the experimental design, we look next at the essential mechanisms known to trigger memory in relation to locations.

C. Applied Theories

The “Dual Coding Theory“ is an influential memory principle proposed by [10]. It explains how the human mind operates with two functionally independent, although interacting, systems or stores, namely *verbal* and *image* memories. The chances that a memory will be retained and retrieved are much greater if it is stored in two distinct functional locations rather than in just one. Paivio updated the theory in 2014 with ’evidence-based suggestions about nourishing mental growth through applications of Dual Coding Theory in education, psychotherapy, and health [11].

In a review of visual memory capacity, [12] proposed a model based on a hierarchy of visual knowledge from object-generic parts to objects-specific parts to the whole object, linking stored knowledge and context-dependent stimuli. This approach explains how visual memory works as an entire associative process connecting new stimuli to stored knowledge and also how visual memory is context and scene dependent. The *context dependent theory* originates with the experiment carried out by [13], in which they compared participants’ performance to recall a list of words within two different natural environments. Results showed that lists of words learnt in a specific place were best recalled when participants were situated in the environment of the original learning.

In their study, [12] also suggest that architecture can be used to anchor that information in a structure linked to previously stored spatial knowledge. As one moves around, starting from birth, one accumulates vast amounts of data about one’s surroundings [14]. Most of this information is processed and abstracted into cognitive maps, which can be accessed at any time to find one’s way or to find an object left behind.

Finally, based on the working memory average digit span for a normal adult of ’seven plus or minus two’, as demonstrated in the study by [15], participants were asked to remember nine random cards in an attempt to avoid reliance on short-term memory.

II. Experimental Design

The broader idea behind our first experiment was to build a VR training system that could be used to enhance one’s memory. We developed an application, ArchiMemory, with the intent to construct a number of places which one can use to organise information. The system was designed to collect movement data from participants navigating the environment. A mixed method approach was selected to gather both quantitative and qualitative data.

In light of these explanations on how human memory works, and with the awareness of the MoL described earlier, it is one of the assumptions of our research that spatial arrangement can be used to extend the human mind by offering a scaffolding to support memory formation and recall.

Indeed, as highlighted in the AoM, the three pillars of memory are imagination, association and location. Imagination and association create new memories. Location helps with the sequencing and anchoring. To that effect, each participant was able to navigate their own route, following a path along the rooms and the frames, and therefore creating their own storyline to support the memorisation of the sequence of playing cards.

The formation of associative memories between a card and an image would support the participant in storing the specific card in memory. The method was to use any associative trigger – like shapes, numbers, colours, metaphorical or allegorical – the participant would think of between an image and the playing card. The participant then had to attach the chosen card to the image.

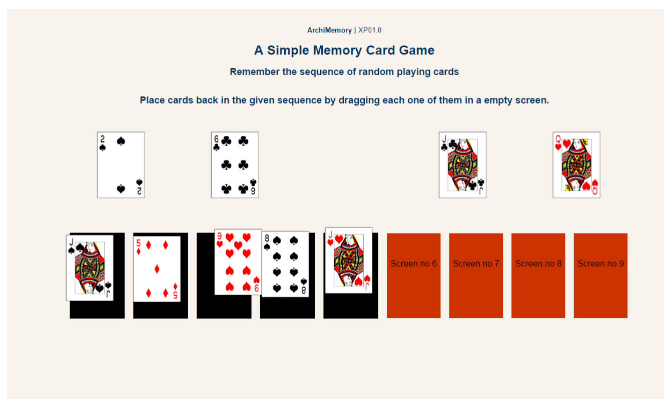

Fig. 1. **Memory Card Game.** The Recall Board shows two rows, the first row with the 9 given cards in order, and the second row with 9 empty slots. In this instance, 5 cards have already been assigned to a slot which become black as opposed to the red rectangle which awaits to be assigned a card.

A. Memory Card Game - Control Group

In the first task, playing cards are displayed on a web page accessed via a computer screen. This is a control task to evaluate participants’ baseline memory capacity before using the mnemonic VR device. The same interface was also used as a *Recall Board* for the player to retrieve the sequence of cards post virtual memory palace experience. Fig. 1 illustrates the display’s look and feel.

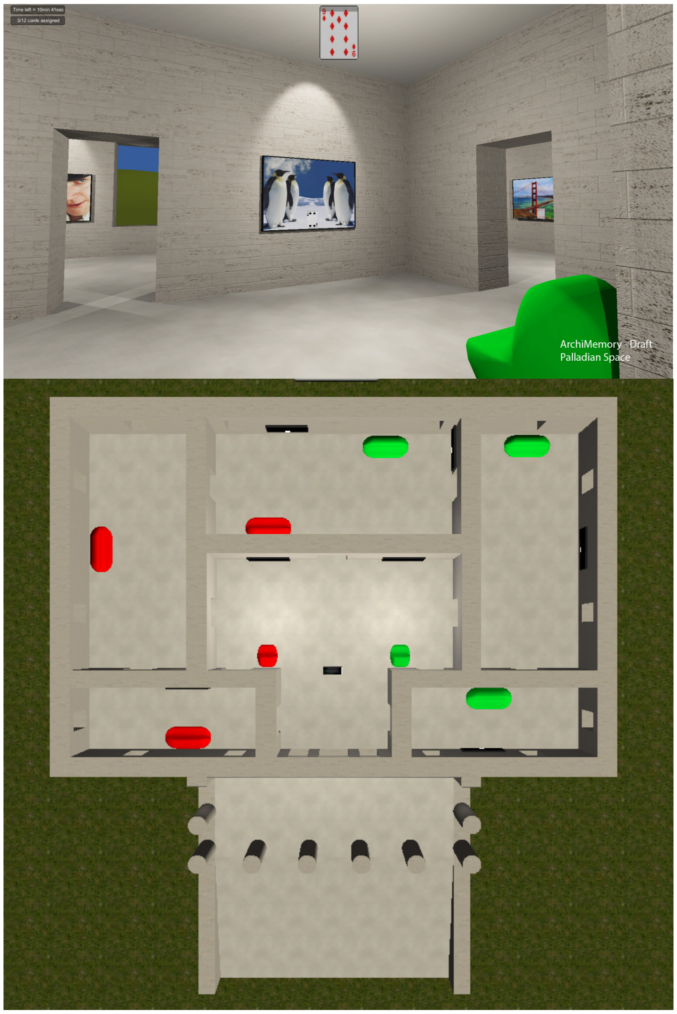

Fig. 2. **The Palladian Palace.** The next playing card appears at the top middle of the screen. On the top left corner is the count of cards already associated.

B. *Virtual Memory Palaces - Two Conditions*

To compare the effect of different styles of architecture on memory performance, two different environments were designed: a Palladian and a Curved Palaces [1].

a) Palladian Palace: It is a typical Palladian plan with multiple interconnected rooms (Fig. 2). Participants had the opportunity to choose their path through the building using a variety of doors. There was no specific direction to follow. Pieces of furniture — red or green sofa, blue carpet, brick walls, table, chairs and plants — were placed in each room.

b) The Curved Palace: This model was an exploration of a design with features seen as in opposition or complementary to the Palladian house, with a much lesser symmetric floor-plan, no sharp corners, no symmetric arrangements of architectural structures like columns (Fig. 3). It was based on the idea of a cave, in which participants could choose between two areas that take them deeper inside the building, ending up in a room with similar furniture to the Palladian option, either green or red. From the main entrance, there was only two path to choose from. The green pieces of furniture were placed in the area following the path to the right, and the red pieces of furniture were placed in the area following the path to the left of a person entering the *cave*.

[1]More environments were designed and tested later on, but not enough results were acquired for reporting in the present paper.

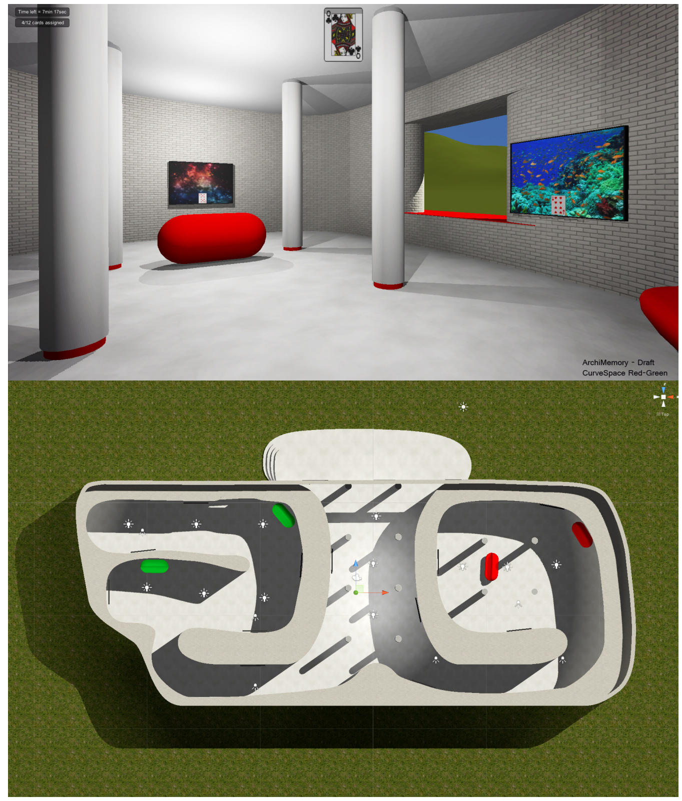

Fig. 3. **The Curved Palace.** The next playing card appears at the top middle of the screen. On the top left corner is the count of cards already associated

III. Materials and Method

A. *Participants*

A total of 18 participants (6 female, 12 male; average age 22.45 years, *SD*=4.23) were recruited from the university student and staff population.

B. *Materials*

a) Memory Card Game and Recall Board: The Memory Card Game was developed with HTML, Javascript, and MySQL. Participants were presented with a computer running Windows on a 20 inch display monitor, a mouse and a keyboard. They used the mouse to interact with the web page on which the memory card game was displayed. It consisted of a deck of cards on which participants could only click to see the next random playing card. After the 9th card, the *Recall Board* showed a first row with the 9 cards in order and a second row with 9 empty slots (Fig. 1). Participants had to place each card in the corresponding slot in the correct sequence. The sequence of cards was then sent to the database (using MySQL) to compare with the given sequence. Participants received the results directly at the bottom of the screen. The nine playing cards were picked from a digital shuffled deck of 52 playing cards. The same images were used inside the virtual environments.

b) Virtual Memory Palaces: Participants were equipped with the Oculus Rift DK2 (as HMD), which had a resolution of 640 x 800 pixels per eye, a refresh rate of 60 Hz and persistence of 3 ms. The position tracking volume covered a square metre including head movements. An XBox controller was used to move around in the virtual environment, which was run on an Intel computer with a dual-core processor, 4 GB of main memory and a Nvidia GeForce 8800GTX graphics card. The frame rate was stable between 45 and 60 frames per second. The real-time rendering was operated on the computer, which was directly connected via cables to the HMD.

c) Heads-up Display: The Heads-up Display (HUD) is frequently used in video games to simultaneously display several pieces of information, such as character health, other items, indication of game progression. In ArchiMemory, it consisted of an opaque top panel showing the current *Playing Card* and a small left panel showing how many cards were already associated and the time remaining to complete the task. Fig. 2 and 3 show the general presentation of the HUD.

d) Navigation Mode: Inside the virtual environment, frames were hanging on the walls. Participant had to use the Xbox controller to navigate the space and go from one frame to the next. They were using the HMD to look around. Once they were close enough of a frame, a random image was shown in the frame, signifying they were now in Frame-Browsing Mode (FBM).

e) Frame-Browsing Mode: The FBM activation was dependent on the participant field of view. The combination of three variables were necessary to activate this mode: angular (θ), horizontal distance (δ), and vertical distance (γ). These variables were obtained using the value of (γ) set as $1.3m < \gamma < 3.0m$.

Participants had to be within a certain range of each of the three variables to activate the browsing mode next to each frame. The sequence of commands to use the Xbox controller, once in FBM, was set using the following keys Key "A" to activate the image on the frame. Key "B" to browse the images. Key "X" to get the last image. Key "BR" (right-trigger button) to confirm the association of image with the card

This mode gave them the opportunity to browse through a series of image organised into five categories: animal, action, landscape, people and theme. They had to select the one they felt was a good match to remember the given playing card.

C. Procedure

All the participants started with the control experiment, using the desktop version of the memory card game. They were then split between the two virtual memory palaces to complete the main task, which was to navigate the virtual environment and associate each playing card with one image inside each one of the located frames hanging on the walls. As soon as they got close enough to one frame, the FBM was activated, a reminder of the controls was displayed on the frame, and from there, they were able to browse through the set of images. Once all the playing cards were associated, they could take a couple of minutes to consolidate the association by navigating the palace. Then they would take the HMD off, access the Recall Board and recall the sequence of playing cards. The details of a session follow.

1) *Control Experiment* (2 min): remember the sequence of random playing cards.
2) *Recall Board* (1 min): recall the sequence by placing the cards in the empty slots of the *Recall Board*.
3) *IVE - Warm up* (2 min): Participants have the opportunity to familiarise themselves with the setup, and discover the IVE with its specific archetype.
4) *Encoding* (10 min): remember a random sequence of 10 playing cards given one by one at the top of the screen (HUD). Participants then have to walk to the next frame, and repeat the same actions.
5) *Consolidation* (2min): When finished associating all the cards, participants take a couple of minutes to revisit the space and consolidate their memories.
6) *Retrieving - Short Term Memory* (1 min): Participants are then presented with the *Recall Board* (same as Control Experiment), which shows the 10 playing cards in order. They are able to move each one of the playing cards visible on the screen into the correct empty slot, following the original sequence. The experiment ends with their score displayed at the bottom of the screen.
7) *Sketching and Questionnaire* (5 min): A five-minute dialogue is usually sufficient to complete a couple of questions which include doing a hand-drawn sketch of the experienced spatial (virtual) layout.

IV. Results

The two hypotheses were (a) that virtual memory palaces support a better memory performance than the desktop solution when attempting to remember a sequence of random playing cards; and (b) different types of architecture have a different impact on memory performance. Quantitative data and analysis are presented first, followed by the qualitative approach.

The data collection was implemented utilising PHP and Javascript functionalities to extract the different types of data from the web application and the Unity Web Player. All of these data were then sent to a MySQL database. Three types of data were collected for each participant: the sequence of cards given and recalled, their positional data, and the images associations. During the control experiment, the sequence of random cards was recorded in a separate table on the database, to be compared later with the sequence recalled by each participant.

Among the 18 participants, one showed unusual behaviour as he/she did not recall any cards after being exposed to the virtual memory palace for the full allotted time of 10 minutes. For that reason, he/she was removed. The rest of the analysis

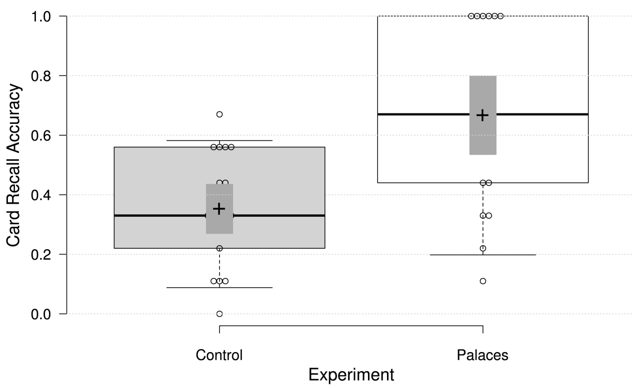

Fig. 4. **Recall Accuracy - Control.** The overall recall performance of participants using a virtual memory palace is about 10% higher compared with the control experiment. Crosses represent sample means recall accuracy percentage: 0.35 for the control experiment and 0.67 for the virtual memory palaces. Centre lines show the medians; box limits indicate the 25th and 75th percentiles as determined by the software R; whiskers extend to 5th and 95th percentiles; bars indicate 90% confidence intervals of the means; data points are plotted as open circles. n = 17 sample points.

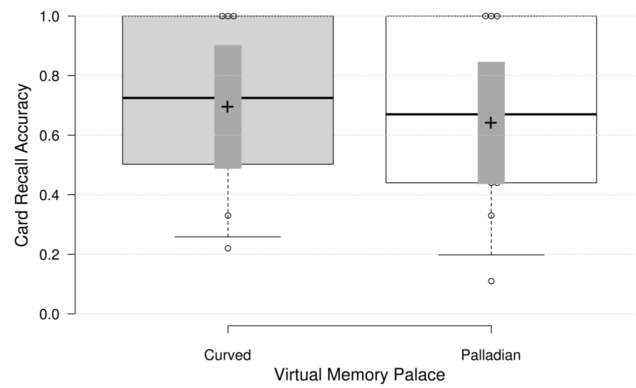

Fig. 5. **Recall Accuracy Between Palaces.** The overall recall accuracy of participants using the the Curved Palace with a mean of 0.70 and Palladian Palace with a mean 0.64 is represented by the crosses. Horizontal lines show the medians; box limits indicate the 25th and 75th percentiles as determined by R software; whiskers extend to 5th and 95th percentiles; bars indicate 90% confidence intervals of the means; data points are plotted as open circles. n = 17.

is based on 17 participants (8 in the Curved Palace, and 9 in the Palladian Palace).

A. Recall Accuracy

The first goal of the study was to examine the recall accuracy differences between a control experiment using a desktop monitor and the virtual memory palaces. Recall accuracy (A) is the ratio of the number of recalled cards to the total number of cards (9):

$$A = RecalledCards/TotalCards$$

Fig. 4 presents a comparison of the overall performance of the users for the control experiment and the overall use of the memory palaces. A one-way ANOVA, which was calculated on participants' recall accuracy, shows a significant difference between the control experiment and the virtual memory palace (F(1; 32) = 12.47, *p*¡0,05).

This result indicates that participants using the virtual memory palaces were better able to recall the sequence of cards than those using a traditional two-dimensional display. The percentage of recall accuracy (i.e. the number of cards recalled in the correct sequence) during the Control experiment was 35% (M = 0.35, SD = 0.20) compared to 67% (M = 0.67, SD = 0.31) for the virtual memory palaces. This represents an increase of 32% in recall accuracy.

The second hypothesis is that different types of architecture have a different impact on memory performance. Fig. 5 presents a comparison of the overall recall accuracy of the users between two different virtual memory palaces. A one-way ANOVA, which was calculated on participants' recall accuracy, shows no significant difference between the two types of virtual memory palace (F(1; 15) = 0.12, *p*=.73).

B. Palace Performance

The time taken for participants to memorise the playing cards was necessary to compare their performances. Each user was allotted 10 minutes to complete all the associations. Fig. 6 shows the distribution of the average time taken inside the two virtual memory palaces. A timer was implemented (visible on the top left corner of the HUD) to give participants some sense of pressure to perform. Even so, variations in the participant behaviours were noted. 10 participants (5 in each condition) were very confident and finished in less than 5 minutes, while the others preferred to take more time and walk around for the maximum time allocated.

A one-way ANOVA shows that difference in the association times between the two palaces was not statistically significant (F(1; 15) = 0.20, *p*=.66). Fig. 6 shows the distribution of the mean time spent in each virtual memory palace to make the nine associations. A noticeable difference is a longer duration of time spent by participants inside the Palladian Palace (M=6.1; SD=1.95) compared with time spent in the Curved palace (M= 5.8; SD=1.32).

Different industries (e.g. user experience, product design, software, supply chain) recognise that cycle time (the duration of a process) is a valuable performance metric to measure process efficiency. In the context of using the MoL as a mnemonic device to enhance memory, the main process comprises forming the associations of the card to be remembered with the trigger image in the situated frame. A good learning method should lead to a more efficient way to remember any given unit of information, so that consequently the system should afford a shorter cycle time. Card cycle time (κ) is defined by the amount of time (in minutes) to successfully record one unit of information (one recalled card):

$$\kappa = time/card$$

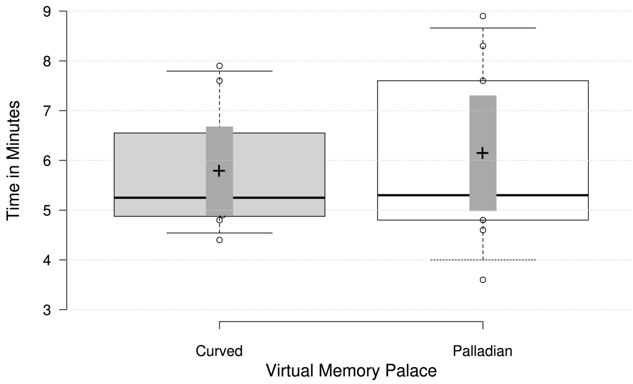

Fig. 6. **Mean Time Comparison between Memory Palaces.** The average amount of time (in min) participants took in each memory palace. Crosses represent sample means of time in minutes: Curved Palace (M=6.1; SD=1.95) and Palladian Palace (M=6.1; SD=1.95). Horizontal lines show the medians; box limits indicate the 25th and 75th percentiles as determined by R software; whiskers extend to 5th and 95th percentiles; bars indicate 90% confidence intervals of the means; data points are plotted as open circles. n = 17.

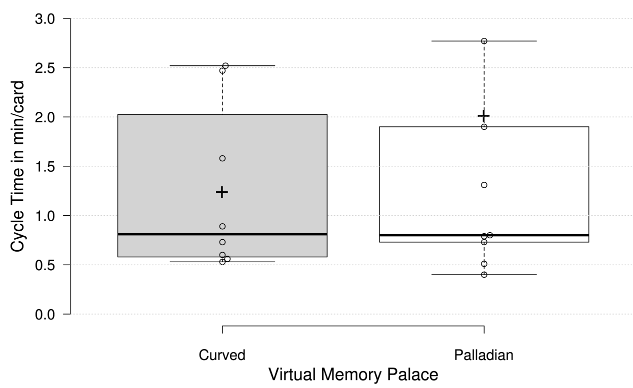

Fig. 7. **Cycle Time Comparison Between Memory Palaces.** The overall cycle time of participants in both virtual memory palaces was approximately equal. Crosses represent sample means cycle time per card: 1.24 in the Curved Palace, and 2.01 in the Palladian Palace. Horizontal lines show the medians almost identical in both case (0.81 in the Curved Palace and 0.8 in the Palladian Palace); box limits indicate the 25th and 75th percentiles as determined using the software R; whiskers extend to 5th and 95th percentiles. n = 17.

A one-way ANOVA shows that the difference in the mean of cycle time between the two palaces was not statistically significant ($F(1; 15) = 0.61$, p=.45). Fig. 7 shows the distribution of the mean cycle time for each virtual memory palace. It is worth noting that in both conditions, 3 participants recalled the 10 playing cards correctly, taking an average of five minutes to memorise them all (κ = 0.5min/card).

To summarise, difference in recall accuracy between the control experiment and the virtual memory palaces (both types) was statistically significant. However, there were no significant differences in recall accuracy between the two virtual memory palaces themselves. From a task performance standpoint, there was a statistical significance in the mean time taken to complete the association process in both palaces. These results show some support in favour of the Curved Palace. Card Cycle time was proposed as a way to evaluate which of the two palaces was more efficient. That said, no statistical significance was demonstrated between the mean of card cycle times.

C. Heatmap Visualisation

A script collected participants' position and movement inside the virtual environments, that is, the time taken by each participant to either explore their surroundings, browse the pictures, and make the associations with the playing cards. One way to visualise these positional data is by representing them on a heatmap. The superimposition of all the heatmaps formed by every participant from one condition can help to understand some common traits, such as the mean path, or the most visited locations. However, these were not used for the purpose of this present analysis.

D. Qualitative Approach: Questions and Sketches

The most unexpected results were revealed by participants' comments and drawings. Of the three questions, the sketched layouts shed the most light on how well people remembered their surroundings, even though they were never asked to do so. Before exploring these drawings, the answers to the two other questions are briefly presented.

The first question was about specific features participants did remember. The different features were: red or green sofa, blue carpet, brick walls, table, chairs and plants. The idea was to understand if one feature exhibited more memory potential than another. Extracting any meaningful patterns from participants' responses was difficult. No particular feature was more cited than another.

For the third question, participants were being asked to explain three associations they formed to help them remember the cards. Due to the content of the pictures used to make these associations, a whole new set of questions were raised and behaviour highlighted, which would have required a different set of investigatory skills related more to sociology or anthropology. Despite the potential interest, this was out of the scope of the present research project.

On the architectural comments, however, a consensus of the participants showed a preference for the Palladian palace. They reported navigating their way with ease, sensing more connections between the rooms, and therefore, creating their own journey. Arguably this is because in our western culture, people have grown up in houses and buildings with mainly orthogonal layouts. This could predispose individuals to be more comfortable processing the similar kind of space.

The results showed, however, that the rational plan of the Palladian palace was less beneficial, even though not statistically significant, to better task performance than in the case of the curved layout. One explanation is that the curved palace offers fewer possible routes (only two) and therefore, supports a linear path more adapted to remembering a sequence of cards. A potential extrapolation would be that a greater choice of paths does not support a more accurate memory performance when using the MoL.

V. Discussion

This section presents the findings of the research goals defined earlier. These are cues in an attempt to answer the broader research question.

a) G1: Identify the rules of the Method of Loci and implement them in VR.: The two books by [2] and [3] were the main inspiration to understand the rules and techniques used to imagine the memory palaces. The rules are not precise but they give some sense to what is important to keep in mind when designing the environments. The following suggestions were applied in the proposed virtual environments.

- There are two kinds of images: one for things, and one for words.
- The environments should not be too similar to each other.
- The space should be of moderate size, at human scale.
- The intervals between the loci should be of moderate extent.

b) G2: Identify the scientific theories behind the Method of Loci and apply them in VR.: The Art of Memory and particularly the Method of Loci are based on mnemonic devices studied in various sub-fields of psychology research. The main theory behind the mechanisms at play when using the MoL are:

- *Working Memory* and the seven plus or minus 2 unit of information. The aim of the MoL is to store the information in long-term memory. As such, there are a minimum of 9 items to remember, to ensure participants reach the maximum capacity of their working memory. Moreover, there are a couple of minutes between the time they exit the virtual environment and when they use the recall board to retrieve the sequence of cards.
- *Context Cueing theory* which shows that information is better retrieved when one is situated in the same place as the recording. The frames on the wall are spatially situated and the user is able to travel back to each one in their mind's eye to visualise the associated card.
- *Association Principle*, which in our case takes the form of the association between the playing card (a number and a colour) to a trigger image that has already some meaning in one's mind and that they can use as part of their own story.

c) G3: Test whether the Method of Loci in VR can improve memory performance.: Findings confirm the hypothesis that using virtual environment-based memory palaces enhances a participant's memory. Overall, participants remembered significantly more cards when using a virtual memory palace than in the desktop-based control experiment.

d) G4: Evaluate the effect of different types of virtual architecture on memory performance.: Two different styles of architecture were tested: a Palladian layout and a Curved walls layout. The Palladian layout offers only straight walls and more than one potential connection between rooms. The Curved wall option offered only two ways, one to the left and one to the right. Participants had to follow the curved corridor to access a larger room at each end. Despite the fact that most of the results were not statistically different, there was a trend toward a shorter cycle time to remember each card from participants who experienced the Curved Palace rather than the Palladian Palace. This could be explained by the benefit of using the *continuity* of the walls to aid recall of the sequence of card in order, compared with the Palladian palace offering too many *connections* between rooms, and thus, confusing efforts when attempting to recall the sequence.

However, participants' comments expressed a preference for the Palladian option. A possible explanation for this conscious preference may lie in the higher symmetry and straightness of the floor plan structure, providing users with a more familiar global frame of reference. For example, the atrium which connects each room, may simplify their spatial representation model, in comparison with a network of curved corridors which provide no symmetries and must be represented in greater local details [17].

Six participants demonstrated a good performance, recalling the 9 cards with a card cycle time of 33sec/card. They confirmed in the post-experiment interviews how this type of method benefits their 'learning style'. It shows that virtual memory palaces work well for some people and less so for others.

e) How can architectural design enhance users' memory performance when using the Method of Loci in VR?: Since 2012, when we initiated the ArchiMemory project, only a handful of studies have begun to examine the potential of VR to study and develop the MoL mnemonic. ArchiMemory was developed over the three following years, during which time we published posts and updates on the website archimemory.net.[2]

The main challenges of virtual environment design are the level of immersion, user interaction, and quality of the spatial design. Our review on the use of VR as a research tool to study spatial cognition, suggests that well designed virtual environments can be used as a medium for new learning methodologies. Our own study, on the basis of the ArchiMemory project, showed the potential of using such a methodology.

In terms of the level of immersion of the VR system used in our experiment, the hardware (dating back to 2014) played an important role in the limitations of the experimental design. The Oculus DK2 consist of a HMD affording a limited positional tracking; as a consequence, participants sat on a chair. The use of an Xbox controller requesting a level of abstraction by mapping translation movement onto buttons also played a role in reducing the level of immersion. Moreover, these factors had the potential to increase the level of motion sickness.

A similar study by [18] showed promising insights into the use of virtual memory palaces. The study showed significant amelioration on memory recall when inside the virtual environment using the HMD compared with a desktop monitor con-

[2]The memory game control experiment was published online in September 2012, and the first version of the virtual environment experiment was released in November 2013. http://archimemory.net

dition using a traditional mouse. In that comparison, in both modalities, participants' position was locked, affording only head rotation. Nevertheless, most of the participants enjoyed the experiment and felt present in the different virtual memory palaces. People's reactions when experimenting with VR was excitement and bewilderment. The more recent generation of HMDs, such as the HTC vive (6DOF) with hand controllers, will help to alleviate previous limitations.

With respect to ArchiMemory, we established the following constraints and questions. The number of connections between rooms, which relates to the potential frame of reference, can have an impact on participants' performance navigating the different palaces. Is it the number of connections in the layout or the lack of global frame of reference that has the biggest effect on the time taken to memorise the sequence of playing cards? The Palladian layout offered an atrium with 5 different passages, compared with the Curved layout, with only 2. This also presents a clearer global frame of reference in the former with more potential paths to choose from, compared with a local frame of reference and only 2 paths to choose from in the latter. It is difficult to know which feature has a significant effect: the number of connections, frame of reference, curved or straight walls. They would need to be measured separately: one experience comparing the difference in the number of connections in the layout; another experience could retain the same layout but compare the *perpendicularity* or *curviness* of the walls. Moreover, further research is needed to identify tools that can quantify the effect of different architectural features.

A mixed method approach was used to gather both quantitative and qualitative data. From a quantitative point of view, one of the limitations in the design was that participants had only one attempt in one memory palace, giving rise to insufficient data points with which to establish a benchmark for each system. Future studies should include a within-subject design and allow multiple (perhaps 5 to 10) trials for each participant. To be able to measure the efficiency of a given system, in this instance a virtual memory palace, each participant would need to use both environments multiple times. A benchmark could then be used to calculate the maximum potential of the system and thus its efficiency. A second limitation was the difficult interpretation of participants' positional data. The heatmaps offered a good visualisation tool but were lacking in terms of measurable outcomes.

VI. Conclusion

To further the results reported in this article, a set of additional studies with a larger population needs to be designed to test the different mechanisms at play when using the MoL in VR. In particular, different architectural layouts and qualities need to be measured in order to more accurately evaluate their effect on users memory performances.

The experiment we reported revealed much insightful information into the potential of using VR not only as a scientific tool but also as a potential mnemonic device to enhance learners' memory performances. VR showed promise as an experimental tool to explore how different types of architecture can possibly affect participants' memory performance. It gave also valuable insights into how users can navigate in VR and how they are able to remember these layouts and sketch them from short term memory. The programming of the interaction within the virtual environment was challenging at times, and linked to the xBox controller and the 6DOF headset with their somewhat limited range of movement. The recent arrival on the market of affordable next generation VR headsets will remove some of these limitations.

References

[1] Eysenck, Michael W (2001). Principles of Cognitive Psychology. Psychology Press, p. 452. isbn: 978-1-84169-260-9.

[2] Yates, Frances A (1966). The Art Of Memory. Random House, p. 474. isbn: 978-1-4481-0413-0.

[3] Buzan, Tony (2006). Master Your Memory. Pearson Education, p. 196. isbn: 978-1-4066-1022-2.

[4] Kosslyn, Stephen M. et al. (1984). Individual differences in mental imagery ability: A computational analysis". In: Cognition 18.1-3, pp. 195.

[5] McCabe, Jennifer A. et al. (July 2013). Psychology Students' Knowledge and Use of Mnemonics". In: Teaching of Psychology 40.3, pp. 183-192.

[6] Susser, Jonathan A. and Jennifer McCabe (May 2013). From the lab to the dorm room: Metacognitive awareness and use of spaced study". In: Instructional Science 41.2, pp. 345-363.

[7] Foer, Joshua (Apr. 2011). Moonwalking with Einstein: The Art and Science of Remembering Everything. en. Penguin UK, p. 339.

[8] Legge, Eric L.G. et al. (Nov. 2012). Building a memory palace in minutes: Equivalent memory performance using virtual versus conventional environments with the Method of Loci". In: Acta Psychologica 141.3, pp. 380-390.

[9] Reggente, Nicco et al. (Mar. 2020). The Method of Loci in Virtual Reality: Explicit Binding of Objects to Spatial Contexts Enhances Subsequent Memory Recall". In: Journal of Cognitive Enhancement 4.1, pp. 12-30.

[10] Paivio, A (1971). Dual coding theory". In:

[11] Paivio, A (2014). Mind and its evolution: A dual coding theoretical approach". In: Mind and Its Evolution: A Dual Coding Theoretical Approach 2007, pp. 1-525

[12] Brady, Timothy F, Talia Konkle, and George A Alvarez (2011). A review of visual memory capacity: Beyond individual items and toward structured representations." In: Journal of vision 11.5, p. 4.

[13] Baddeley, Alan D. and Graham Hitch (1974). Working Memory". In: Psychology of Learning and Motivation. Vol. 8, pp. 47-89.

[14] Piaget, Jean (Sept. 1964). Part I: Cognitive development in children: Piaget development and learning". In: Journal of Research in Science Teaching 2.3,pp. 176-186.

[15] Miller, Henry (1957). Big Sur and the Oranges of Hieronymus Bosch. New Directions Publishing, p. 420.

[16] Schneider, Walter and Jason M. Chein (2003). Controlled and automatic processing: Behavior, theory, and biological mechanisms". In: Cognitive Science 27.3, pp. 525-559.

[17] Werner, Stephen and Paul Long (2002). Cognition Meets Le Corbusier—Cognitive Principles of Architectural Design". In: Spatial Cognition III. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 112-126.

[18] Krokos, Eric, Catherine Plaisant, and Amitabh Varshney (Mar. 2019). Virtual memory palaces: immersion aids recall". In: Virtual Reality 23.1, pp. 1-15.