Vol.6 Special Issue No.1 (2024)

Journal of Applied Learning & Teaching

ISSN : 2591-801X

Content Available at : http://journals.sfu.ca/jalt/index.php/jalt/index

Design and development of MemoryTrail virtual reality game to study brain and memory processes in a fun and interactive manner

Rasyiqah Bte Shaik Mohamed Salim[A]
Jacob Shihang Chen[B]
Chen Huei Leo[C]
Bina Rai[D]

[A] *Department of Biomedical Engineering, National University of Singapore, Singapore*
[B] *Office of Digital Learning, Singapore University of Technology & Design, Singapore*
[C] *Science, Math & Technology, Singapore University of Technology & Design, Singapore, Center for Healthcare Education, Entrepreneurship and Research (CHEERS), Singapore University of Technology & Design, Singapore*
[D] *Department of Biomedical Engineering, National University of Singapore, Singapore*

Keywords

Brain anatomy and nervous system;
design validation;
motivation and memory;
serious games;
serious game design and assessment framework;
virtual reality (VR).

Correspondence

biebr@nus.edu.sg [D]

Article Info

Received 14 June 2023
Received in revised form 27 July 2023
Accepted 29 July 2023
Available online 1 August 2023

DOI: https://doi.org/10.37074/jalt.2023.6.S1.3

Abstract

We designed and developed a virtual reality game, MemoryTrail VR, to learn about brain anatomy and the nervous system using a serious games design and assessment framework with a focus on purpose that was reflected in five elements: content, fiction and narrative, mechanics, aesthetics and graphics, and framing. We added a sixth element, motivation and memory, with the aim to bridge the gap between student engagement and the content being taught and, in doing so, aid in the retention of knowledge. This was executed through the introduction of knowledge interweaved in a storyline that was relatable to our undergraduate students from a local university in Singapore. The 21-item questionnaire data validated that MemoryTrail VR was a serious game designed with components which were mainly coherent and cohesive with its purpose. We found that using a structured framework to design and evaluate the game enabled us to collate meaningful feedback and identify specific areas for improvement for the next version of the game with the goal of eventually developing a serious game that is theory- and evidence-driven. There was a significant increase in the percentage of students who answered conceptual questions correctly when comparing the pre- and in-game quizzes, providing evidence of learning achieved by the students because of the gameplay.

Introduction

Current pedagogical approaches to teaching undergraduate students about the fundamental concepts surrounding brain structure and function are limited to the use of textbooks, videos, and lectures. In biology, lecturing has been reported to promote memorization of facts rather than fostering deep understanding in most students, and even high academic achievers sometimes gain little understanding of basic biology concepts via traditional lectures (Sundberg, 2002). To overcome these limitations, studies have emerged that investigate the efficacy of using digital teaching tools such as virtual reality (VR) for the visual appreciation of anatomy (Abdullah et al., 2021; Codd & Choudhury, 2011; Latini & Ryttlefors, 2020; Singh et al., 2019). VR enables interactions in a 3D environment that makes the learning experience immersive and relatable as compared to 2D alternatives (Dick, 2021), allows students to be more engaged with the content (Bonasio, 2019), and enhances retention of knowledge (Ekstrand et al., 2018).

We found several applications of VR for medical education in Singapore, including a dental anaesthesia simulation designed by the Keio-NUS CUTE Center (Yen et al., 2018), a VR in agitation management game developed by the NUS YLL School of Medicine (Bharade, 2022), AI virtual humans created by MediVR (*InteractAI Virtual Human*), and Project Polaris (to practice clinical procedural skills) developed by the NUS YLL School of Medicine in collaboration with Microsoft (*Microsoft*, 2022). Their motivation for adopting VR was so that experiential learning would be more accessible to their students, to train students in clinical soft skills such as ethics and communication and clinical anatomy, to introduce realistic clinical scenarios and in a low-risk setting. Specifically for learning brain anatomy, there is a VR Brain Exploration application developed by Sidequest. This game allows students to navigate within the brain and examine its subcomponents, which helps them to gain a deeper understanding of the structures and their positions in the brain (*VR Brain Exploration*, 2021).

Despite the efforts to create meaningful immersive experiences, sometimes VR games fail to sustainably engage students and/or result in knowledge retention (Rai et al., 2019). Serious games are digital games and simulation tools that are created for non-entertainment use but with the primary purpose of improving the skills and performance of play-learners through training and instruction (Loh et al., 2015). There are two considerations that are often overlooked when designing a serious game for education. The first is motivation – why do people play? There are several motivational theories; a notable one is the Self-Determination Theory (SDT), which explains the human motivation to perform an activity as being internally driven (Ryan & Deci, 2000). Crafting a motivational game using SDT and its subcomponents requires that players feel they are autonomous and in control of their own actions, that they experience competence in achieving the tasks within the game space, and that they feel somehow related to others who are either playing the game with them at that moment or who have played before.

The second often neglected consideration is episodic memory, which is information stored in a person's long-term memory that receives and stores information about temporally dated episodes or events and temporal-spatial relations among those events (Deci et al., 1999). Episodic memories are stored in such a way that each memory is identified by a personal "tag." Typically, such memories are recalled through association with a particular time or place and tend to be vivid as they are recalled (Malone, 1981). Often it is difficult to remember what was discussed or reviewed in class, but it is far easier to recall the look of the classroom, the position of the instructor's desk, and the location of the door. In a well-designed serious game, episodic memory provides the learner with the ability to recall the elements of the game or the game environment. With games, the visual cues are established in the mind of the learner, and if the experiences are geared toward real-life applications, then the memories of the learner will be strong and associated with what he or she needs to do in a particular location (Kapp, 2012).

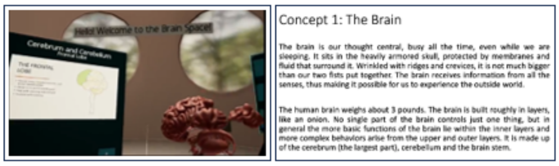
To address the above challenges, our team sought to design and develop a VR simulation to learn about the brain and nervous system using a Serious Games Design and Assessment (SGDA) framework with a focus on purpose that is reflected in five elements: content, fiction and narrative, mechanics, aesthetics and graphics, and framing (Mitgutsch & Alvarado, 2012). We added a sixth element, motivation and memory, with the aim to bridge the gap between student engagement and the content being taught and, in doing so, aid in the retention of knowledge. This was executed through the introduction of knowledge interweaved in a storyline that is relatable to our undergraduate students living in Singapore. Concepts were tagged to different junctures of the story. We hypothesise that through the inclusion of a story in the game design, the narrative would be able to provide a sensory experience that helps with students' engagement, thus improving their ability to understand and relate to the content. The simulation ends with a series of conceptual questions as the player cycles back to the starting point. A playtest was conducted on undergraduate students from a local university who completed a pre- and in-game quiz to determine the extent of learning and a design validation questionnaire with items relating to the six elements mentioned above.

Methodology

Game design

We adopted a step-by-step approach to designing the serious game, MemoryTrail VR, taking into consideration six game components that were carefully aligned with the purpose. (Mitgutsch & Alvarado, 2012).

Table 1: The purpose and six game components of MemoryTrail VR.

Components	Description
Purpose	The learning objective of MemoryTrail VR was for learners to gain knowledge about brain anatomy, the nervous system, and their function, with the aim of enhancing knowledge retention by incorporating game elements that trigger motivation and episodic memory. The goal of MemoryTrail VR was for the learner to cycle from the meeting point to the final destination by following the instructions and engaging in dialogue with the non-player characters. To arrive at the final destination, the learner must be able to answer a series of multiple-choice questions (conceptual) correctly.
Content and information	A designated environment was created within the game called the BrainSpace, which contains information about the different parts of the brain and the nervous system and their functions. There were seven concepts covered that include the brain, brain stem, cerebrum and cerebellum, limbic system, neuron, synaptic transmission, and nervous system. Learners could touch and dismantle the different parts of the 3D brain structure (refer to screenshots below). Each part was linked to its name and function in the form of a note.  Learners were transported into this space at specific junctures according to the narrative, for example in Scene 1, "Two friends decided to cycle from East Coast Park to Gardens by the Bay. This was part of a new scenic route in Singapore, the Eastern Coastal Loop. They met at a coffee place at Marine Cove, grabbed breakfast, planned their route, and started to cycle from there." The following question then appears, "How are we able to do all these things such as talk, move and function?" This was the trigger to transport the learner into the BrainSpace to gain information about concepts 1-3. We used corrective and immediate feedback that guided the learner toward the correct instructional outcome. This was designed in the form of multiple-choice questions (MCQs) at the end of the scenario, where the learner must answer ten questions correctly before he/she can race back to the final destination. The learner was provided with unlimited attempts and brought back to the BrainSpace to refer to the concepts if he/she answered incorrectly.
Game mechanics	The game was designed to be based on discovery, where learners find new information through sequential activities. Questions were introduced to stimulate curiosity amongst our learners and to lead them into the content. We spaced the information out proportionally over the six scenes. The game space consisted of specific spots along the bicycle trail and the BrainSpace. 3D objects were created to represent typical objects that you will find at a coffee place, park and ice cream stall. Learners could interact with the objects by pointing and clicking on it.
Fiction and Narrative	The storyline of the game followed the experience of two friends embarking on a bicycle ride along East Coast Park, starting from Coffee Bean at Marine Cove and arriving finally at Marina Bay Sands. The story consisted of six scenes (refer to screenshots below). An element of fun was injected in Scene 5 when the avatar showed off by cycling without hands, to impress the non-player character (NPC). An element of chance/tension was created in Scene 6 when a personal mobility device (PMD) rider suddenly appears, nearly knocking into the NPC. The ending scene was depicted as a competitive "race" between the two friends as they strive to reach their endpoint. The narrative ended happily and on a positive note. This narrative was chosen as it is an activity that is relatable to Singaporean young adults.  The learner played the role of the avatar who was the main cyclist. The NPCs were the second cyclist (the avatar's friend), local ice cream seller (scene 3), and PMD rider (scene 6). These were all dynamic characters with whom the learner engaged with via dialogues, both written and audio.
Aesthetics and graphics	The game was set in a realistic, 3D virtual environment of a bicycle trail along East Coast Park, Singapore. The route that the player took was adapted from the map of the Eastern Coastal Loop, with the starting point from Coffee Bean at Marine Cove and ending at Marina Bay Sands (refer to screenshots below). The whole environment was recreated from scratch in Unreal Engine based on a series of 360 photos taken during a site visit at the initial stage of the project, and GIS data from OpenStreetMap. 
Framing	The content of the game was framed for first year undergraduate students, both with and without a prior biology background. The content targeted the lower levels of Bloom's Taxonomy, namely remembering, understanding, and applying. The immersive and hands-on experience was designed to engage kinaesthetic learners. The narrative and dialogue were targeted at student learners between the ages of 18-22 and Singaporeans.
Motivation and Memory	Game elements and dynamics were designed to fulfil the three psychological needs, competence, autonomy and relatedness (derived from the Self-Determination Theory) to trigger intrinsic motivation in the learners. Learners were given the autonomy to explore the environment at their own pace and proceed to the various scenarios only when they were ready to do so. We tried to bring in relatedness by using familiar NPCs and environments. Competence was determined using conceptual questions. We designed the narratives to stimulate episodic memory in the learner, which are memories tied to strong emotions and are recalled through association with a particular time or place and tend to be vivid as they are recalled. Here are two examples. In Scene 3, "The two friends decide on the path to take and continue cycling towards Gardens by the Bay. Ten minutes later, the characters see an ice cream seller by the side of the path and stop. The ice cream man recognized character 1 and asked him how he has been. Both of them bought the mixed ice cream with bread and sat down on a bench to eat it. Character 2 asks character 1 how he knew the ice cream man. Character 1 shares that this ice cream man brings back sad memories for him. His ex-girlfriend and him used to cycle and stop by at this ice cream man regularly." In Scene 4, "The two friends finished their ice cream and felt happy. It was a beautiful day! Character 1 said that he was glad that they decided to go on this cycling trip together and appreciates his friend's company. In fact, he was beginning to develop feelings for his friend."

Game development

MemoryTrail VR was built using Unreal Engine 4 software, a powerful, feature-rich, open-source game engine with high levels of customizability. Blueprints (Unreal Engine's visual scripting system), C++ and Python were used to build the VR interaction systems along with the backend that collects and consolidates the data from the playtest. Microsoft Azure's text-to-speech feature was utilised to generate the voiceovers and dialogues used in the game. The building of the game occurred in stages. Firstly, the background environment of the game was designed and created. This included the building of different structures, characters, and objects. We then proceeded to design the individual scenes of the game. Finally, the dialogue for each scene was added in, and all components were packaged together.

Playtest

A playtest was conducted on 53 undergraduate students from a local university in Singapore. The game setup included a VR-ready laptop and an HP Reverb G2 VR Headset and controller (Figure 1). Each gameplay lasted for about 15 minutes. After the completion of the game, the students were asked to fill up a design validation questionnaire via google forms. It contains 21 items, as detailed in Appendix A. These items covered the six components of the SGDA framework and motivation and memory. Students rated their experiences based on a Likert Scale ranging from 1 - 5 and an open-ended question to allow for detailed feedback. Before the start of the game, the students were asked to complete a quiz on brain anatomy and function deployed with Kahoot (Appendix B). It consisted of 11 conceptual questions and was used to determine the baseline of the students' knowledge of the concepts to be covered. After completing the scenarios, students attempted ten MCQs within the game and will have to answer all questions correctly to cycle back to the final destination. If the student had selected the wrong answer, they were prompted to try the question again. This was repeated until the student selected the correct answer. If a wrong answer was selected, students were also given the option to re-visit the concepts in the BrainSpace before trying the question again. MCQs were assigned randomly from a pool of 34 questions (Appendix C). The in-game quiz scores were compared against the pre-game data to determine if the students acquired new knowledge.

Figure 1: Photographs of students during the playtest of MemoryTrail VR.

Statistical analyses

Group mean values were analysed by either Student's unpaired test or one-way ANOVA with post hoc analysis using Tukey's test as appropriate using Graphpad Prism 6 software (GraphPad, San Diego, CA, USA). All data were presented as mean ± standard deviation (SD). Statistical significance was considered when the p-value was <0.05.

Results and discussion

Design validation questionnaire

After playtesting the game, the students completed the design validation questionnaire, consisting of 21 items (including three open-ended questions). The overall survey data revealed a total score of 69.3/90, demonstrating that the students tended to agree (neutral to agree range; 54-72) that the game elements were aligned with its purpose (Figure 2). Next, the questions relating to the different components of the adapted SGDA framework were critically analysed.

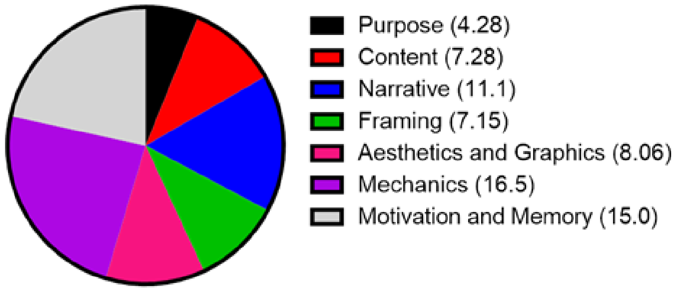


Figure 2: Pie chart illustrating the overall respective scores for each design validation component in the parenthesis.

We found that for the question related to the purpose (question 1, Appendix A), the game scored a score of 4.28/5, indicating that most of the students agreed that they were aware of what the game was testing them (Figure 2). Furthermore, for questions relating to the content, narrative, framing and aesthetics and graphics (Figures 3A-D), the game had a combined score of 7.28/10, 11.1/15, 7.15/10 and 8.06/10, respectively (Figure 2). These results suggest that students were neutral and tended to agree (>3.5 out of points on the Likert scale) that the content, narrative, framing and aesthetics of the game were coherent and cohesive to the purpose (Figure 3A-D).

Open-ended feedback revealed that students were engaged, could relate, and enjoyed flipping through the brain factsheet. While the purpose and content of the game were clear to them, it was suggested that the storyline could be more realistic or that there could be a clearer link between the storyline and educational content. It was proposed that more leading questions could be added in immediately after the concepts were shared. There was a suggestion that the dialogue could be made more relatable by using recordings of actual people rather than using an AI-generated voice (Table 1). Another feedback was to break down the concepts into specific functions instead of the general functions of each region of the brain and nervous system.

Regarding the mechanics of the game (Figure 4A), the game scored 16.5/20 (Figure 2). This showed that the students mostly agreed that the game was easy enough to navigate and the instructions were clear and easy to follow. Moreover, students provided feedback that they liked the narrative of the game and the relatability of the storyline. There was a suggestion to add more scenes so that the narrative and concepts could be intertwined better. Lastly, for questions pertaining to motivation and memory (Figure

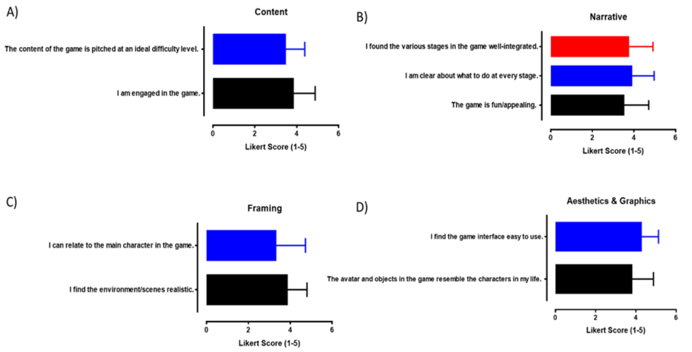


Figure 3: Likert score of the individual questions within the different components for design validation, including A) content, B) narrative, C) framing and D) aesthetics and graphics. All data were presented in mean±SD, n=53.

Table 2: Examples of students' open-ended feedback from the playtest questionnaire.

Student	Feedback
1	"game narrative is relatable and cute to university students"
2	"I feel that the narrative of the game is generally relatable in the Singaporean context where cycling is quite a common activity."
3	"The narrative helps to allude to the next concept. Can also insert questions related to the concept for player to answer immediately after introducing the concept. E.g. which part of the brain controls my hands - make the player answer the question"
4	"It helps reinforce the concepts"
5	"I liked the idea of flipping through the brain factsheet – but I think it needs to be clearer that players should click 'back to the real world' immediately, because I would have continued on to click next instead of the real-world button"
6	"can make the game feel more real by having more real looking characters/ environment"
7	"The narrative is too robotic and did not feel like I was talking to a person, also, I was not given a choice to interact with the person. Might be good if I am able to talk to the person with choices of response given to me."
8	"I did not understand the point of the narration. It could have been better linked to the content."

4B), the game had a score of 15.0/20 (Figure 2), suggesting that the students were neutral or tended to agree that they felt motivated to play the game and that it triggered their memory. Specifically, for questions 19 and 20, which asked if students felt that they were granted autonomy in the game or if they would play the game again, the game scored 3.45±1.28 and 3.64±1.23, respectively. Similarly, based on open-ended feedback, students felt that they would have preferred more freedom to make choices in the game. This could be because the game was designed in a linear manner where each scene would play consecutively. The players were not allowed to make decisions at each juncture of the game whether to proceed or not, and this may have reduced autonomy.

In summary, the overall questionnaire data validated that MemoryTrail VR was a serious game designed with components which were mainly coherent and cohesive with its purpose. We found that using a structured framework to design and evaluate the game enabled us to collate meaningful feedback and identify specific areas for improvement for the next version of the game. Our findings concur with Verschueren et al. (2019), who reported that the establishment of a well-defined framework that represents the consensus views of the serious games for the health

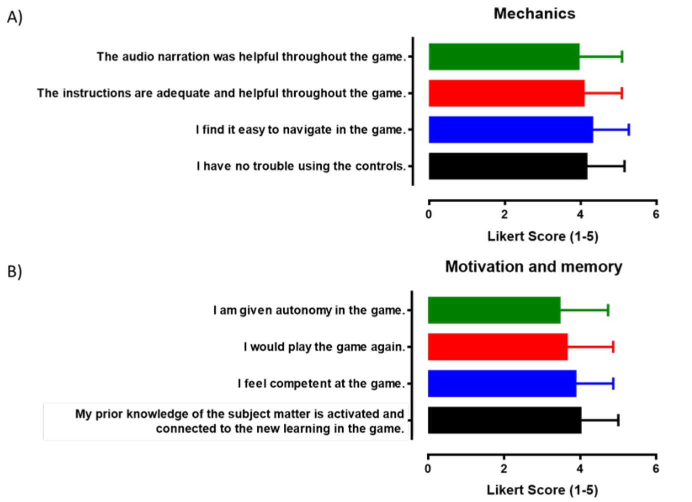


Figure 4: Likert score of the individual questions within the different components for design validation, including A) mechanics and B) motivation and memory. All data were presented in mean±SD, n=53.

research community would help developers improve the efficiency of internal development processes, as well as the chances of success. A consensus framework would also enhance the credibility of such games and help provide quality evidence of their effectiveness. We went a step further to include an additional component of motivation and memory that proved to be important, and we received feedback on how to improve our learners' motivation to play. For example, allowing for more autonomy for the players as they navigate the game. Notably, data on the perceived competence was encouraging and will be useful for us to gauge any improvements during iterative evaluation.

Assessment of learning outcomes from gameplay

As the purpose of the MemoryTrail VR game was to facilitate students' learning of brain anatomy and memory concepts, we needed to verify that learning was indeed achieved via the gameplay. A series of MCQs were used to assess the various concepts, as listed in Appendix C. A pre-game quiz administered using Kahoot was used to determine pre-existing knowledge, and it was observed that for the majority of the questions, less than half of the students were able to answer the questions correctly. It was noted that the weakest concepts were the parts of the neuron and its functions, the limbic system, and the cerebrum and cerebellum. Subsequently, the students completed MemoryTrail VR and were assessed using randomly assigned MCQs within the game derived from the same MCQs pool.

Overall, by comparing the mean percentage of students who answered the questions correctly between the pre-game and in-game quizzes, there was a significant ($p = 0.0044$) increase (25.7%) in the mean percentage of students who answered the questions correctly for the in-game quiz, suggesting that the students were able to acquire concepts related to brain and memory through the gameplay (Figure 5A). While there was a significant increase in the overall mean percentage of students who answered the questions correctly, we noted that not all the questions were consistently improved, as some of the questions were answered incorrectly by the students even after the gameplay. From Figure 5B, out of the ten questions tested, there were six questions (questions 1, 2, 3, 7, 22 and 23) that a greater proportion of students answered correctly during in-game after the first attempt compared to students answering those questions during the pre-game quiz. MemoryTrail VR was designed to allow learners to make errors, and they were given the chance to revisit concepts and progress in the game after multiple attempts and finally answer the questions correctly. Interestingly, it was observed that most of the students were able to answer all of the questions correctly by their second attempt in the in-game quiz (Figure 5B).

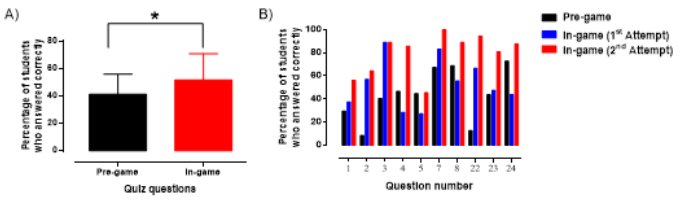


Figure 5: A) Percentage of students who answered questions correctly in the pre-game and in-game quizzes. B) Percentage of students who answered ten questions correctly in pre-game and in-game quizzes during their first and second attempts. All data were presented in mean±SD, * Significantly different from pre-game, unpaired Student's t-test, P<0.05, n=41-47.

To further determine which concepts of the brain and memory were acquired during the gameplay, we examined the percentage of students who were able to get the questions correct during their first, second or third attempts. Based on Figure 6A, we noted that for the 17 questions pertaining to the parts of the neuron and its functions, 56.5±12.6% of students who attempted the questions were able to get the question right on their first attempt. There was a significant improvement in the percentage of students that were able to answer the questions correctly by their second attempt (79.8±16.6%) and third attempt (90.8±12.2%). For the set of five questions relating to the nervous system, 65.2±27.5%, 89.4±10.1%, 93.3±6.5% of students were able to get the correct answer by their first, second, and third attempts, respectively. While the improvement was still observed after the second or third attempt, there was no statistical significance observed as the percentage of students who obtained the questions correctly was more variable at the first attempt (Figure 6B).

For the set of eight questions testing the parts of the brain and its functions, 42.9±25.8% of students answered the question correctly on their first attempt (Figure 6C). Furthermore, 67.4±13.3% and 88.9±8.3% of the students answered the questions correctly after the second and third attempts, respectively, which was a significant improvement from the first attempt. Similarly, for questions on the limbic system, cerebrum, and cerebellum, 52.7±12.3% of students answered the question correctly in their first attempt, with significant improvements after the second and third attempts (Figure 6D). Taken together, it was evident that

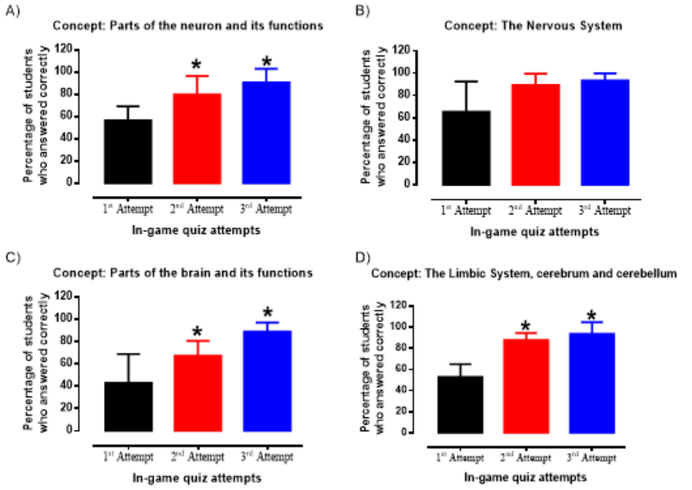


Figure 6: Percentage of students who answered in-game quiz questions correctly at first, second or third attempts to concepts pertaining A) parts of the neurons and functions, B) the nervous system, C) parts of the brain and its functions and D) the limbic system, cerebrum, and cerebellum. All data were presented in mean±SD, * Significantly different from the in-game first attempt, One-way ANOVA, Tukey's post-hoc test, P<0.05, n=3-17.

the majority of the students were able to select the correct answer on the second attempt for the question.

Our results verified that there was indeed evidence of learning achieved by the students because of the gameplay, specifically the significant increase in the percentage of students who answered questions correctly when comparing the pre- and in-game quizzes. We can conclude that MemoryTrail VR enabled students to understand, remember, and recall the concepts covered, as compared to their knowledge of the content before playing the game. Interestingly, results showed that students tended to do better for questions on the nervous system and limbic system. A possible explanation for this could be that the nervous and limbic systems were the last concepts to be covered before the students attempted the quiz. Another explanation could be that the nervous and limbic systems were more concise segments, thus allowing the students to digest the content easily, as there was less information to process at one time.

Conclusions

The result of this research demonstrated that the design and development of the MemoryTrail VR using an adapted Serious Games Design and Assessment (SGDA) framework was able to enhance the learning process of undergraduate students with respect to engagement, fun and learning outcomes. The various game elements enabled students to understand and appreciate the concepts and subsequently apply the knowledge gained during the quiz in an interactive manner. This study also highlighted the importance of adopting a structured approach towards the design of digital-based learning solutions that could help to guide the validation process to obtain meaningful feedback. Based on the data obtained, we will reflect on the various components and make refinements to the current version of MemoryTrail VR with the goal of eventually developing a serious game that is theory- and evidence-driven.

Acknowledgements

The research was funded by SUTD Pedagogy Innovation Grant (2020-1061SC). The authors would like to acknowledge student game developers Chen Yiyang and Rui Bian for their contribution towards the early development of the MemoryTrail VR game. The sponsor has no role in the study design (in the collection, analysis, and interpretation of data or in the writing of the report) and in the decision to submit the article for publication. The corresponding author would like to acknowledge Ivan Boo from Serious Games Association for the discussions about a standardised serious games design and assessment framework and how to apply it for evaluation.

References

Abdullah, E., Lone, M., Cray, J. J., Dvoracek, P., & Balta, J. Y. (2021). Medical students' opinions of anatomy teaching resources and their role in achieving learning outcomes. *Medical Science Educator, 31*(6), 1903-1910. https://doi.org/10.1007/s40670-021-01436-2

Bharade, A. (2022, May 26). Keep calm and carry on: Virtual reality helps medical and nursing students manage agitated patients with empathy. *Press Release*. https://medicine.nus.edu.sg/wp-content/uploads/2022/05/2022-05-26-Press-Release-Virtual-Reality-in-Agitation-Management.pdf

Bonasio, A. (2019). Immersive experiences in education. *Microsoft*. https://edudownloads.azureedge.net/msdownloads/MicrosoftEducation_Immersive_Experiences_Education_2019.pdf

Codd, A. M., & Choudhury, B. (2011). Virtual reality anatomy: Is it comparable with traditional methods in the teaching of human forearm musculoskeletal anatomy? *Anatomical Sciences Education, 4*(3), 119-125. https://doi.org/10.1002/ase.214

Deci, E. L., Koestner, R., & Ryan, R. M. (1999). A meta-analytic review of experiments examining the effects of extrinsic rewards on intrinsic motivation. *Psychological Bulletin, 125*(6), 627-668. https://doi.org/10.1037/0033-2909.125.6.627

Dick, E. (2021). The promise of immersive learning: Augmented and virtual reality's potential in education. *Information Technology and Innovation Foundation,* 1-23. https://itif.org/publications/2021/08/30/promise-immersive-learning-augmented-and-virtual-reality-potential/

Ekstrand, C., Jamal, A., Nguyen, R., Kudryk, A., Mann, J., & Mendez, I. (2018). Immersive and interactive virtual reality to improve learning and retention of neuroanatomy in medical students: A randomized controlled study. *CMAJ Open, 6*(1), E103-E109. https://doi.org/10.9778/cmajo.20170110

InteractAI Virtual Human. (2023). https://www.interactai.live/

Kapp, K. (2012). *The gamification of learning and instruction: Game-based methods and strategies for training and education*. (1st ed.). Pfeiffer & Company.

Latini, F., & Ryttlefors, M. (2020). Teaching anatomy to neuroscientific health-care professionals: Are they receiving the best anatomical education? *Medical Science Educator, 30*(1), 41-45. https://doi.org/10.1007/s40670-019-00838-7

Loh, C. S., Sheng, Y., & Ifenthaler, D. (2015). *Serious games analytics*. Springer International Publishing. https://doi.org/10.1007/978-3-319-05834-4

Malone, T. W. (1981). Toward a theory of intrinsically motivating instruction. *Cognitive Science, 5*(4), 333-369. https://doi.org/10.1207/s15516709cog0504_2

Microsoft News Center. (2022, January 11). *Medical education goes holographic with mixed reality from Microsoft*. https://news.microsoft.com/en-sg/2022/01/11/medical-education-goes-holographic-with-mixed-reality-from-microsoft/

Mitgutsch, K., & Alvarado, N. (2012). Purposeful by design?: A serious game design assessment framework. In *Proceedings of the international conference on the foundations of digital games* (FDG '12) (pp. 121-128). ACM. http://hdl.handle.net/1721.1/100701

Rai, B., Tan, H. S., & Leo, C. H. (2019). Bringing play back into the biology classroom with the use of gamified virtual lab simulations. *Journal of Applied Learning & Teaching, 2*(2), 48-55. https://doi.org/10.37074/jalt.2019.2.2.7

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist, 55*(1), 68-78. https://doi.org/10.1037/0003-066X.55.1.68

Singh, K., Bharatha, A., Sa, B., Adams, O. P., & Majumder, M. A. A. (2019). Teaching anatomy using an active and engaging learning strategy. *BMC Medical Education, 19*(1), 149-149. https://doi.org/10.1186/s12909-019-1590-2

Sundberg, M. D. (2002). Assessing student learning. *Cell Biology Education, 1*(1), 11-15. https://doi.org/10.1187/cbe.02-03-0007

Verschueren, S., Buffel, C., & Stichele, G. V. (2019). Developing theory-driven, evidence-based serious games for health: Framework based on research community insights. *JMIR Serious Games, 7*(2), e11565. doi:10.2196/11565

VR Brain Exploration. (2021). https://sidequestvr.com/app/5442/vr-brain-exploration

Yen, C.-C., Lee, M., Foong, W. C. K., Low, G., & Lau, J. H. (2017). *Dental anaesthesia simulation*. https://cutecenter.nus.edu.sg/projects/dental-anaesthesia-sim.html

Appendices

Appendix A: Design validation questionnaire.

No.	Question	Answer Type	Component
1	I know what the game is testing me.	Likert scale – 1 to 5	Purpose
2	I am engaged in the game.	Likert scale – 1 to 5	Content
3	The content of the game is pitched at an ideal difficulty level.	Likert scale – 1 to 5	Content
4	The game is fun/appealing.	Likert scale – 1 to 5	Fiction/narrative
5	I find the environment/scenes realistic.	Likert scale – 1 to 5	Framing
6	I can relate to the main character in the game.	Likert scale – 1 to 5	Framing
7	The avatar and objects in the game resemble the characters in my life.	Likert scale – 1 to 5	Aesthetics and graphics
8	I am clear about what to do at every stage.	Likert scale – 1 to 5	Fiction/Narrative
9	I found the various stages in the game well-integrated.	Likert scale – 1 to 5	Fiction/Narrative
10	Do you have any feedback on the narrative of the game?	Open ended	Fiction/Narrative
11	I have no trouble using the controls.	Likert scale – 1 to 5	Mechanics
12	I find it easy to navigate in the game.	Likert scale – 1 to 5	Mechanics
13	The instructions are adequate and helpful throughout the game.	Likert scale – 1 to 5	Mechanics
14	The audio narration was helpful throughout the game.	Likert scale – 1 to 5	Mechanics
15	I find the game interface easy to use.	Likert scale – 1 to 5	Aesthetics and graphics
16	Do you have any feedback on the overall aesthetics of the game?	Open ended	Aesthetics and graphics
17	My prior knowledge of the subject matter is activated and connected to the new learning in the game.	Likert scale – 1 to 5	Motivation and memory
18	I feel competent at the game.	Likert scale – 1 to 5	Motivation, and memory
19	I would play the game again.	Likert scale – 1 to 5	Motivation and memory
20	I am given autonomy (a lot of freedom) in the game.	Likert scale – 1 to 5	Motivation and memory
21	Do you have any other feedback for us regarding the game?	Open ended	

Appendix B: Pre-game quiz questions on brain anatomy and function.

No.	Question	Concept
1	The cell that acts to relay electrical information to other nerve cells is a (n) ____.	Parts of the neuron and its functions
2	The neurons that are located in the brain and spinal cord are ____.	Parts of the neuron and its functions
3	Glial cells perform all of the following functions EXCEPT ____.	Parts of the brain and its functions
4	The role of the postsynaptic neuron in neural communication is to ____.	Nervous system
5	A myelin sheath functions to ____.	Parts of the neuron and its functions
6	The spinal cord ____.	Parts of the brain and its functions
7	Which brain structure controls learning, memory and emotions?	The cerebrum and cerebellum
8	Which brain structure plays a central role in homeostasis?	The limbic system
9	Which part of the brain coordinates motor movements and some spatial skills?	The cerebrum and cerebellum
10	Which part of the neuron contains the nucleus (where transcription and translation happens)?	Parts of the neuron and its functions
11	Which lobe of the cerebrum is involved in judgment and problem-solving?	The cerebrum and cerebellum

Appendix C: In-game quiz questions on brain anatomy and function.

No.	Question	Concept
1	The cell that acts to relay electrical information to other nerve cells is a(n) ____.	Parts of the neuron and its functions
2	The neurons that are located in the brain and spinal cord are ____.	Parts of the neuron and its functions
3	Glial cells perform all of the following functions EXCEPT ____.	Parts of the brain and its functions
4	The role of the postsynaptic neuron in neural communication is to ____.	The Nervous system
5	A myelin sheath functions to ____.	Parts of the neuron and its functions
6	During action potential conduction along a myelinated axon, the action potential appears to jump from ____.	Parts of the neuron and its functions
7	The spinal cord ____.	The Nervous system
8	Which part of the neuron contains the nucleus (where transcription and translation happens)?	Parts of the neuron and its functions
9	Where are neurotransmitter receptors located?	Parts of the neuron and its functions
10	Neurotransmitters affect postsynaptic cells by	Parts of the neuron and its functions
11	Functionally, which cellular location is the neuron's "decision-making site" as to whether or not an action potential will be initiated?	Parts of the neuron and its functions
12	The following steps refer to various stages in transmission at a chemical synapse. 1. Neurotransmitter binds with receptors associated with the postsynaptic membrane. 2. Calcium ions rush into neuron's cytoplasm. 3. An action potential depolarizes the membrane of the axon terminal. 4. The ligand-gated ion channels open. 5. The synaptic vesicles release neurotransmitter into the synaptic cleft. Which sequence of events is correct?	Parts of the neuron and its functions
13	The surface on a neuron that discharges the contents of synaptic vesicles is the	Parts of the neuron and its functions
14	The fastest possible conduction velocity of action potentials is observed in	Parts of the neuron and its functions
15	In the communication between a motor neuron and a skeletal muscle,	Parts of the neuron and its functions
16	The point of connection between two communicating neurons is called	Parts of the neuron and its functions
17	In certain large animals, this type of neuron can extend beyond 1 meter in length.	Parts of the neuron and its functions
18	The nucleus and most of the organelles in a neuron are located in the	Parts of the neuron and its functions
19	A simple nervous system	The Nervous system
20	The divisions of the nervous system that have antagonistic, or opposing, actions are	The Nervous system
21	Preparation for the fight-or-flight response includes activation of the ________ nervous system.	The Nervous system
22	Which brain structure plays a central role in homeostasis?	The limbic system
23	Which part of the brain coordinates motor movement and spatial skills?	The cerebrum and cerebellum
24	Which lobe of the cerebrum is involved in judgment and problem-solving?	The cerebrum and cerebellum
25	Calculation, contemplation, and cognition are human activities associated with increased activity in the	Parts of the brain and its functions
26	Which of the following shows a brain structure correctly paired with one of its primary functions?	Parts of the brain and its functions
27	If you were writing an essay, the part of your brain that would be actively involved in this task is the	Parts of the brain and its functions
28	The establishment and expression of emotions involves the	Parts of the brain and its functions
29	Failure of an embryonic neuron to establish a synaptic connection to another cell	Parts of the neuron and its functions
30	Short-term memory information processing usually causes changes in the	Parts of the brain and its functions

31	Learning a new language during adulthood alters activity in the brain's language processing locations by	Parts of the neuron and its functions
32	Forming new long-term memories is strikingly disrupted after damage to the	Parts of the brain and its functions
33	When Phineas Gage had a metal rod driven into his frontal lobe, or when someone had a frontal lobotomy, they would	Parts of the brain and its functions
34	Which of the following structures or regions is incorrectly paired with its function?	Parts of the brain and its functions