Evaluating the impact of multimodal Collaborative Virtual Environments on user's spatial knowledge and experience of gamified educational tasks

Doumanis, I. and Economou, D.

This is a copy of the author's accepted version of a paper subsequently published in the proceedings of the 6th International Conference of the Immersive Learning Research Network. OnLine, 21 - 25 Jun 2020, doi:10.23919/iLRN47897.2020.9155165

The final published version is available online at:

https://dx.doi.org/10.23919/iLRN47897.2020.9155165

Evaluating the impact of multimodal Collaborative Virtual Environments on user's spatial knowledge and experience of gamified educational tasks

*Note: Sub-titles are not captured in Xplore and should not be used

line 1: 1st Given Name Surname
line 2: *dept. name of organization*
(of Affiliation)
line 3: *name of organization*
(of Affiliation)
line 4: City, Country
line 5: email address or ORCID

line 1: 4th Given Name Surname
line 2: *dept. name of organization*
(of Affiliation)
line 3: *name of organization*
(of Affiliation)
line 4: City, Country
line 5: email address or ORCID

***Abstract*—Several research projects in spatial cognition have suggested Virtual Environments (VEs) as an effective way of facilitating mental map development of a physical space. In the study reported in this paper, we evaluated the effectiveness of multimodal real-time interaction in distilling understanding of the VE after completing gamified educational tasks. We also measure the impact of these design elements on the user's experience of educational tasks. The VE used reassembles an art gallery and it was built using REVERIE (Real and Virtual Engagement In Realistic Immersive Environment) a framework designed to enable multimodal communication on the Web. We compared the impact of REVERIE VG with an educational platform called Edu-Simulation for the same gamified educational tasks. We found that the multimodal VE had no impact on the ability of students to retain a mental model of the virtual space. However, we also found that students thought that it was easier to build a mental map of the virtual space in REVERIE VG. This means that using a multimodal CVE in a gamified educational experience does not benefit spatial performance, but also it does not cause distraction. The paper ends with future work and conclusions and suggestions for improving mental map construction and user experience in multimodal CVEs.**

Keywords— collaborative virtual environments; virtual human; avatars; mental map; spatial performance; user experience; gamification.

I. Introduction

People generally acquire knowledge of space without any concentrated effort. They can use this mental map to find and follow routes from one place to another and to store and use the relative positions of places. It's this knowledge which enables people to follow or to think up new and shorter routes to familiar destinations and to point toward places they cannot see. Many studies into spatial cognition within VEs have shown that there is a little difference in the way representations of spaces are formed compared to real-world environments[1][2]. As an example, the research reported in [3] showed that a Virtual Environment (VE) could be used to train participants to follow a designated route almost as effectively as in a real-world environment. Other studies have shown that learning activities in VEs can help users develop or improve (e.g., in cases of rehabilitation) their spatial ability [4][5][6].

There is plenty of evidence in the literature that 3D VEs can foster spatial knowledge of spaces in human users. However, there are very few studies investigating the impact of multimodal real-time interaction on the user's spatial knowledge after completing gamified educational tasks in a VE [7]. Gamification is about integrating game mechanics and metaphors to a non-game application to engage and motivate users to complete their intended goal [8]. Game mechanics, such as competition, awards, exploration, if used properly in a task hold the potential to increase user motivation, engagement and enjoyment. Because of the increased user engagement with the task, users could develop a better mental awareness of the environment, a mental map closer to the actual environment. Furthermore, multimodal real-time interaction involves some or all human senses (e.g., vision and hearing) when interacting with the environment and others in Collaborative Virtual Environments (CVEs). This rich sensational interaction combined with real-time simulation responses produces a deeper feeling of immersion [9], which could further enhance the impact of gamification.

To test this hypothesis, we developed research instruments that allowed conducting an experiment to compare the spatial knowledge acquired by users completing educational tasks in a multimodal CVE (namely Virtual Gallery) versus a multimedia web platform (namely Edu-Simulation [10]) (see section III). In the web platform users had to complete educational tasks using a panoramic photorealistic representation of a real-world gallery. The virtual gallery was developed using the REVERIE framework [11][12]. REVERIE is a multimedia and multimodal framework designed to facilitate the development of VEs featuring multiple modalities of interaction (e.g., fully puppeted virtual human, spatial 3D audio, replicas, emotion recognition, etc.). It can also support the creation of tasks in VEs featuring several gamified elements. Edu-Simulation is a web platform that allows the organisation and dissemination of educational material, organisation of students in groups, synchronous and asynchronous communication that can be used to organise any role play simulation scenario. The study was also interested in measuring the user experience of educational tasks with each prototype.

The remaining of the paper is organized as follows: Section II explains the theoretical underpinnings of this research by elucidating the characteristics of spatial knowledge; Section III describes the prototypes that have been developed to assist the study; Section IV covers the experimental approach and provides a detailed account of the user trials, research environment, and goals; Section V presents results and data analysis and discusses the lessons learned from this project and the paper ends in Section VI with future work and conclusions.

II. THEORETICAL FRAMEWORK

A mental map can be defined as *"long-term stored information about the relative location of objects and phenomena in the everyday physical environment"* [13]. Any mental map may contain a mixture of information received at different time periods. It may also contain incomplete, more or less schematic or distorted information given at a particular point in time. Researchers have identified four stages of perceiving a physical space [14]:

- *Stage 1*: A perceiver has a vague awareness of the environment. In particular, s/he is aware of the existence of sensory information coming from somewhere in the environment. At this stage, the perceiver may expect that this initial sensory information may relate to a perceived physical structure, location or potential use of objects.
- *Stage 2*: A perceiver adds spatial characteristics to the perceptual set. An object is given a location in the physical space and is classified into a category of objects with similar spatial attributes. At this stage, perceivers start to differentiate among objects by their spatial attributes.
- *Stage 3*: Involves recognising and specifying the relevant attributes (e.g., identity, size, condition, etc.) of the perceptual objects. Such attributes become differentiating characteristics from one object to another in the same class.
- *Stage 4*: Involves the identification or the attachment of meaning to a perceived object. The meaning and significance a perceiver attach to an object determines its durability and usefulness. Once an object becomes an easily recognisable entity, it will start occupying a regular place in an individual's cognitive structure. Also, the newly identified object along with other members of the set can be used as a reference point to evaluate and match new stimuli.

A technique for recovering information about environments is a hand-drawn sketch map [15]. A sketch map is an outline of an environment drawn from observation rather than from exact survey measurements. The information users record on a sketch map can reflect their perception of space, which should match either the last stage of the framework (identification of objects) or any of the stages before. In the study reported in this paper, we used sketch maps and the theoretical framework to measure spatial knowledge of the two environments represented by different methods of representation (multimodal CVE versus panoramic photorealistic photographs).

III. RESEARCH INSTRUMENTS

Two prototypes have been developed to address the needs of the study allowing to compare the spatial knowledge acquired by users taking part in an educational activity interacting in a multimodal CVE versus a multimedia control.

A. The virtual gallery prototype using REVERIE

The REVERIE framework [11][12] was used to implement an educational scenario which immersed users in a virtual gallery (see Fig. 1). The REVERIE VG features an immersive 3D environment with a collection of historical and art objects (e.g., David by Michelangelo and Woman with parasol) and GUI elements (e.g., a list of participants, a feature menu). In this educational scenario participants interacted with each other to complete gamified tasks within the VE. Represented as virtual humans (VHs), they could explore REVERIE VG, communicate with other participants in a multimodal manner (e.g., using spatial 3D sound and non-verbal communication) and create multimedia files (e.g., video of a session) to share with other people.

Fig. 1: The REVERIE Virtual Gallery (VG) Scenario

The REVERIE avatar authoring tool (RAAT) [17] enabled students to create ad-hoc VH, while teachers were represented by a default VH (avatar). Sessions in REVERIE VG were moderated by the teacher assigned to each group who carried out a wide variety of tasks including giving students permission to speak, monitor and prevent cyberbullying and others.

B. The multimedia control using Edu-Simulation

The Edu-Simulation web platform (see Fig. 2) is a Web e-learning environment which offers a range of features similar to the REVERIE framework (e.g., role-playing, voting among students, the formation of groups, etc.) allowing the users to conduct the same educational tasks as on REVERIE VG.

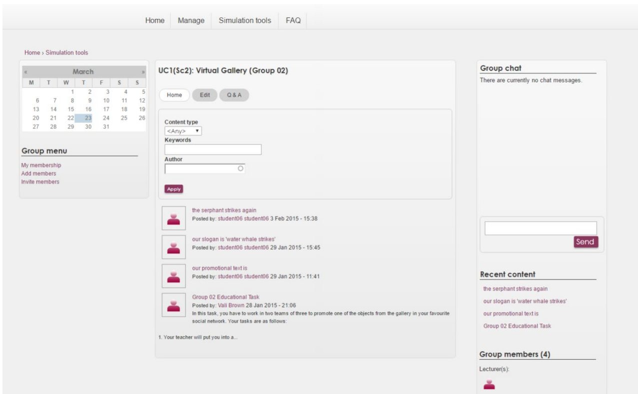

Fig. 2: The Edu-Simulation educational platform

The web platform includes a menu bar representing the learning scenarios (or simulations) that can be accessed by the users. Users can communicate with each other using a text-based group chat and by posting in forums. As on REVERIE VG teachers can monitor interactions between students and intervene when needed (e.g., to prevent cyberbullying). For the study, we uploaded an interactive panoramic application of the Mona Lisa Gallery in the museum of the Louvre in Paris. The virtual gallery loads in a separate window while the main platform runs in the background.

IV. EXPERIMENTAL APPARATUS

The study was planned to evaluate the spatial knowledge acquired by participants when completed a gamified educational task using a multimodal CVE versus a conventional multimedia web platform. Additionally, we wanted to evaluate the user experience of the multimodal CVE. The success of REVERIE VG in conveying spatial knowledge will depend on the usability of the system and the cognitive accessibility of the educational task. For users to successfully develop a perception of the virtual space (matching the four stages of the theoretical framework covered in Section II) should be able to cognitively process the information conveyed by the VE and complete assigned task successfully, investing small effort [18]. Information in REVERIE VG can be expressed through multiple modalities of communication and multimedia artefacts (e.g., recorded videos shared between users, VH gestures, etc.) [19]. The educational task required participants to explore the virtual gallery to locate specific objects and to talk about them. The following section discusses the experimental setting.

A. Overview

A controlled environment was set up for conducting the study simulating an actual classroom environment in two schools in the UK. Participants that took part at the study performed the same educational tasks.

The following variables have been manipulated:

- the type of interaction (multimodal CVE vs multimedia Web);
- the type of educational content (multimodal vs multimedia);
- the type of educational activity (group vs individual);
- the order of prototypes to observe any practice effects.

Participants completed the educational tasks using a desktop computer and a keyboard and a wireless mouse as input devices. To communicate and experience spatial sound in the VE users wore a Bluetooth headset, while a web camera has been used to track users' head and facial expressions while interacting in REVERIE VG. Users were offered training at the start of the testing session to get familiar with the use of the system. All user sessions were recorded on HD video. Four researchers were present in the study to record and provide the necessary technical and logistical support.

Four hypotheses have been formed and tested:

H1: The use of a multimodal CVE fosters the development of a better mental map of the virtual space than the multimedia Web platform. This is because the multimodal real-time interaction and gamification aids user engagement and immersion. Increased user immersion makes it easier for users to become more aware of the virtual space, which increases their chances of identifying desired objects in the environment.

H2: Subjective satisfaction is higher in the multimodal CVE irrespective to the type of educational activity (group or individual). The use of multiple modalities of interaction enhances natural communication among teachers, students and their peers. In addition, the gamified environment and educational tasks influence positively fun and enjoyment of the learning experience.

H3: The multimodal CVE can foster the development of "better" presentation skills in group tasks. This is because the use of multimodal real-time interactions can enhance the group's mental scaffolding process.

H4: Edu-Simulation excels in individual tasks that involve public presentations. This is because the web-platform provides an environment where users feel safe to express themselves using text messages without been affected by the immediacy of a speech-based system.

B. Participants

In total, 42 secondary school teachers and students aged between 11 to 18 took part in this study and were randomly assigned to the study conditions. Each group had a mix of 6 male and female students and one teacher. All participants were English-speakers (either native or as a second language) and had a variety of familiarity with video games and social networking media (e.g., Facebook, Twitter, etc.)

C. Measures and Methods

The user experience was measures with a set of objective and subjective measures.

1) Objective Measures

Usability was measured objectively as **effectiveness**, represented by the task completion rate, user error, rating and sketch maps, while **efficiency** was measured by the time needed to complete a task:

- **Tasks completion rate** is the number of users who completed the educational activities over the total number of participants codes as 1 when successful or 0 for task failure.
- **User error** is when users: (a) did not choose the appropriate method (e.g., the correct UI button to increase the volume) to reach their task goal (UE1), (b) did choose the appropriate method to reach their task goal but did not use the method correctly (e.g., were not able to position their VH as requested in front of an object) (UE2) [20].
- **Rating** measures the points awarded to students for their presentations. The total number of students rating their peers was considered as a measurement representing the effectiveness of each prototype in enabling this core individual task of the educational activity.
- The average **time** (in seconds) each user needed to complete the assigned tasks with the prototypes (REVERIE VG and Edu-Simulation).
- **Sketch maps** were used to evaluate the user's spatial understanding of the virtual spaces they experienced using the prototypes (REVERIE VG and Edu-Simulation). After completing an activity, participants were asked to sketch a map on a sheet of paper illustrating the virtual space and the locations of objects in it. There were told to ignore the aesthetics of the map and focus on trying to fully represent what they could recall.

2) Subjective Measures

Satisfaction, was evaluated using a Post-Study System Usability Questionnaire (PSSUQ) [21]. The first questionnaire used a seven-point Likert scale (1=strongly disagree, 7 = strongly agree). The questionnaires intended for teachers and students were of the same type, but differed in length and complexity. Questionnaires intended for students included fewer and less complex questions compared to the ones intended for teachers. The four questionnaires had the following format:

- **Questionnaire 1**, used a mixed format (binary and open-ended) questions, and it was designed to subjectively assess the user's spatial knowledge of the virtual gallery. It required participants to indicate (yes/no) if they saw specific objects in the Virtual Gallery and to recall their names.
- **Questionnaire 2**, was designed to address the usability of the prototypes using an adapted version of the standardised PSSUQ questionnaire [21].
- **Questionnaire 3**, assessed the cognitive accessibility (CoA) [22] of the educational tasks completed with the prototypes. It addressed the user satisfaction in completing the educational activities.
- **Questionnaire 4**, was divided into two areas: (1) one addressing qualities of the user's virtual representation (VH, e.g., fidelity, realism, etc.,) and (2) qualities of the 3D objects (e.g., realism, believability, etc.).

After the completion of a session, users were asked to participate in a 5-10 minutes group interview that included questions based on observations made by the researchers during the study. The questions were open-ended and gave participants the chance to express their views about the prototypes and offer suggestions about future improvements.

D. Educational Tasks

An educational task was designed which required students to give a presentation about a selected object that could be found either in REVERIE VG or Edu-Simulation. Students had to complete the activity either individually or in groups. To assist students with their presentations, teachers provided a printed card containing information about the object and questions for students to consider answering in their presentations. To complete each task participants had to use the interactive tools available on each system (e.g., look-alike VHs on REVERIE VG and group chat on Edu-Simulation). Tasks were gamified by adding game mechanics such as exploration, rewards and competition.

In the ***individual task***, students had to present an object to their classmates to inform them about its artistic and cultural value. The individual activity had the following format:

- the teacher assigned a card with an object to the first student;
- the student had to locate their assigned object in the virtual space;
- when the student found the object s/he had to give a presentation;
- after the presentation students had to rate it using a point-based system;
- after students had finished presenting; the teacher announced the student with the highest points as the winner of the educational activity.

In the ***group task***, the teacher divided the class into two groups and assigned each student at random a card with information about an object. Each group had to decide which of the objects they preferred, and they had to compose a short descriptive text to be associated with the object. To complete each activity students had to use the communication tools available on each platform. The group activity had the following format:

- each group of students discussed the objects they preferred;
- students had to collaborate to compose a descriptive text for the object they worked;
- once a group was ready, a representative from each group had to present the descriptive text;
- the teacher had to review each group's descriptive text, provide feedback and decide on the winner of the educational activity.

E. Experiment Conditions

The study followed a mixed factorial design, manipulating the type of system (REVERIE VG vs Edu-Simulation) and type of interaction (multimodal CVE vs multimedia Web) as within-participants variables (see Table 1). To reduce transfer effects participants were asked to complete a different version of the educational task (Group or Individual) with each system. We also measured the impact of task variation (Group vs Individual) as a between-participants variable.

The participants were assigned to conditions at random counterbalanced with respect to system type and task version: 1) REVERIE VG with group task vs Edu-Simulation with individual task or 2) REVERIE VG with individual task vs Edu-Simulation with group activity or 3) Edu-Simulation with individual activity vs REVERIE VG with group activity or 4) Edu-Simulation with group activity vs. REVERIE VG with individual activity.

TABLE 1: EXPERIMENTAL DESIGN

Participants (N = 42)	**REVERIE VG (Multimodal CVE)**	**Edu-Simulation (Multimedia Web)**
1 – 9 Students (+ 1 teacher)	*Group Activity*	*Individual Activity*
10 – 18 Students (+ 2 teachers)	*Individual Activity*	*Group Activity*
	Edu-Simulation (Multimedia Web)	**REVERIE VP (Multimodal CVE)**
19 – 28 Students (+ 2 teachers)	*Individual Activity*	*Group Activity*
29 – 36 Students (+ 1 teacher)	*Group Activity*	*Individual Activity*
Dependent Variables	*Objective and subjective measures/ Spatial Performance*	

V. RESULTS AND DISCUSSION

A. Objective Assessment

1) Completion Rate:

The completion rate of participants with both prototypes was 100%. However, due to the fact that both prototypes have a Technological Readiness Level (TRL) of 6 and training was given at the beginning of each session this cannot be credited to the design of the prototypes. Hence, it can be concluded that both prototypes were effective in enabling participants to complete the educational tasks they have been assigned, but this was partially due to the design of the experimental study.

2) Total Time:

Table 2, shows the average time required to complete the assigned educational tasks. A two-factorial ANOVA taking time as the dependent variable, and order of systems and the type of task (group vs individual) as independent variables showed that the average time (in seconds) to complete the assigned educational tasks was not different as a function of any of the variables.

TABLE 2: TIME (SECONDS) AS A FUNCTION OF TYPE AND ORDER OF SYSTEMS

Type of System	REVERIE VG vs. Edu-Simulation (N = 42)	Std. Deviation	Edu-Simulation vs. REVERIE VG (N = 42)	Std. Deviation
REVERIE VG	1458	152.7	1130	523
Edu-Simulation	1380	212.1	1280	395.9

Participants spend almost the same amount of time completing tasks using the prototypes. This shows that none of the prototypes had any impact (positive or negative) on time required to complete the assigned tasks. This could be due to the simplicity of the UI of both prototypes.

3) User Errors

An analysis of the video files revealed the following about the way participants interact with the prototypes:

REVERIE VG

- Most students had problems avoiding colliding their VHs in REVERIE VG (UE2).
- Out of the 6 students, 3 had problems positioning their VH in front of an object as requested. For example, when students were requested to form groups in different areas of the virtual gallery, they had problems getting into a proper group formation facing each other and holding a reasonable distance from each other's VH (UE2).
- Out of the 6 students, 3 had problems understanding the size of the artefacts in the virtual space. As a result, when they had to gather around an artefact to listen to a presentation, they would either walk very close to the artefact or stand far away (UE1).

Edu-Simulation

- Out of the 6 students, 3 had problems finding the required pages on Edu-Simulation to complete the assigned tasks (UE2).

4) Ratings

When students experienced the individual educational activity on REVERIE VG, they rated for all their peers (36/36). However, when they experienced the individual educational activity on Edu-Simulation not all students rated each other (27/36). This shows that the interaction modalities used by REVERIE VG were more effective in enabling students to rate other students. Students could use multiple senses (e.g., vision, hearing) to identify their peers and simple GUI elements to easily cast and keep track of their votes. On the other hand, on Edu-Simulation they had to browse through multiple posts with long text to identify and rate their peers without having access to an easy method of tracking and awarding points.

5) Spatial Knowledge

Maps were ranked for completeness on a scale of 1-4 (reflecting the requirements of the four stages of perception described in Section II) by two experienced user experience experts. The UX experts were given a description of the stages of perception based on which they were asked to evaluate the completeness of each map. They were asked to overlook the drawing quality of the maps and rate them according to how well they depict the VE and the objects' locations within it. Table 3, shows the average ratings the researchers gave per prototype. Students were able to develop more than a vague awareness of the environment and add spatial characteristics to objects on both systems. A one-way ANOVA test did not reveal any significant differences in the way students perceived the VEs on the two systems. It is evident that multimodality alone cannot guarantee enhanced spatial understanding. Thus, **H1** about the benefits of multimodal CVE (see Section IV) should be rejected, as the use of a multimodal CVE did not result in improved spatial performance for students. This was confirmed by the group interviews that suggested that if the system allowed students to interact with artefacts (e.g., select them and closely examine them) they would most likely have specified relevant attributes and meaning (stage 3 and 4 of the theoretical framework) in their sketch maps.

TABLE 3: MAP COMPLETENESS AVERAGE RATINGS

Type of System	Average ratings	Std. Deviation
REVERIE VG	1.6875	0.592289
Edu-Simulation	1.4375	0.618922

B. Subjective Assessment

1) Object-Recognition Questionnaire

The left column of Table 4, shows the total number of objects teachers and students recognised in the Virtual Gallery. Teachers recognised a high number (75%) of objects in the virtual space, but they were able to attach meaning to only 42% of them. Students recognised 77% of the objects they encountered in the virtual gallery and were more successful (49.5%), compared to their teachers, in attaching meaning to the objects. A logistic regression to determine whether the type of task (group vs individual) had an effect on recognising and attaching meaning to objects in the VE showed no significant effects. This indicates that completing the educational tasks was more important in recognising and attaching meaning to objects in the VE. It also suggests that it was equally difficult for participants to recall the names of objects in both tasks. The difficulty in recalling names provides a possible explanation about why students were not able to develop more than a vague awareness of the REVERIE VG space (see spatial knowledge).

TABLE 4: OBJECT RECOGNITION RESULTS

Gallery Objects (Y/N)	Teachers (N = 6)	Students (N = 36)
Recognised	27/9	166/50
Attached Meaning	15/21	107/109

2) Usability Questionnaire (Teachers Only)

We first analysed the teachers' ratings across the three usability qualities of both systems. A one-way ANOVA revealed a significant main effect of type of system on the information quality (F (1, 70 = 10,920; p < .05). It also showed an effect of system on the interface quality (F (1, 94 = 5,781; p < .05). Teachers rated both qualities (mean InfoQual = 5.58 and mean InterQual = 5.29) of Edu-Simulation higher than REVERIE VG. A possible explanation for why teachers rated both qualities of Edu-Simulation higher could be due to the use of text.

TABLE 5: TEACHERS MEAN USABILITY RATINGS

Qualities	REVERIE VG	Std. Deviation	Edu-Simulation	Std. Deviation	Sig.
System Quality	5.10	1.12	5.43	1.38	.228
Information Quality	4.31	1.88	5.58	1.36	.002
Interface Quality	4.52	1.50	5.29	1.63	.018

Teachers may have felt that the information provided about the educational activities is clearer in text format rather than in multimodal format. Additional ANOVA comparisons for each questionnaire item did not show any effect of the independent variables.

3) CoA Questionnaire (Teachers Only)

There were no statistically significant differences between group means as determined by one-way ANOVA comparing the effect of system type on the self-assessment cognitive accessibility scores (see Table 6). Hence, the second hypothesis of the study (see **H2** in Section IV) about REVERIE VG evoking better user satisfaction compared to Edu-Simulation should be rejected at least related to how teachers experienced the educational tasks on the two systems. Additional ANOVA comparisons considering the questionnaire items did not show any effect for task variation or task completion order.

TABLE 6: TEACHERS MEAN RATINGS OF COA ACROSS REVERIE VG AND EDU-SIMULATION

Qualities	REVERIE VG	Std. Deviation	Edu-Simulation	Std. Deviation
The organisation and implementation requirements of the educational task	4.67	1.20	4.88	1.33
Input Modalities	4.25	1.89	5.04	1.27
Feedback Mechanisms	5.00	1.36	5.25	1.46
Short Term Memory Requirements	4.75	1.71	4.47	1.76
Emotional Responses	5.22	1.00	5.33	1.28
Long Term Memory Requirements	4.53	1.35	4.25	1.68
Building a Mental Map	4.42	1.38	4.33	1.53
User responses	4.12	1.91	3.83	1.63
Complex user responses	4.63	1.79	4.87	1.73

4) CoA and usability (Students Only)

As opposed to teachers, students rated the REVERIE VG usability higher compared to Edu-Simulation. An ANOVA test showed that the effect of system type on self-assessment was significant for interface quality (F (1, 70) = 5.573, p < .05). Teachers rated the interface quality of REVERIE VG (mean REVERIE VG = 5.0) higher than Edu-Simulation (mean Edu-Simulation = 4.17). Students may have thought that the game-like environment of REVERIE VG is more suitable to complete the task and showed preference to the UI quality of REVERIE VG.

TABLE 7: STUDENTS MEAN USABILITY RATINGS

Usability Qualities	REVERIE VG	Std. Deviation	Edu-Simulation	Std. Deviation	Sig.
System Quality	5.28	1.3	4.72	1.8	.147
Information Quality	3.25	1.5	3.56	1.7	.426
Interface Quality	5.0	1.4	4.17	1.5	.021

Students on average rated the CoA of REVERIE VG more positively than the one of Edu-Simulation. The descriptive statistics below show that the gamified educational activities (individual and group) worked better on the first rather than the latter.

TABLE 8: STUDENTS MEAN COA RATINGS ACROSS REVERIE VG AND EDU-SIMULATION

CoA Qualities	REVERIE VG	Std. Deviation	Edu-Simulation	Std. Deviation	Sig.
Organisation and implementation requirements of the educational task	4.22	1.5	4.19	1.2	.933
Input Modalities	4.06	1.5	3.33	1.4	.049
Feedback Mechanisms	3.61	1.6	4.08	1.3	.194
Short Term Memory Requirements	4.77	1.4	4.77	1.3	1.00
Emotional Responses	5.27	1.7	4.75	1.7	.200
Long Term Memory Requirements	4.14	1.3	4.70	1.5	.102
Building a Mental Map	4.97	1.3	3.53	1.2	.000
User responses	3.11	1.1	3.50	1.1	.160
Complex user responses	4.25	1.3	4.02	1.3	.504

A series of one-way ANOVA tests showed a significant effect on the following CoA qualities:

- Building a Mental Map (F (1, 70) = 37.556; p < .001);
- Input Modalities (F (1, 70) = 4.010; p < .05).

It was easier for students to use the available modalities on REVERIE VG (mean REVERIE VG = 4.0) than on Edu-Simulation (mean Edu-Simulation = 3.33). Students felt that it was easier to build a mental map of the virtual space on (mean REVERIE VG = 4.9) than on Edu-Simulation (mean Edu-Simulation = 3.05). The REVERIE VG provided an environment where students could explore and learn about objects in the environment in a game-like way (e.g., to navigate using a map). This finding validates our hypothesis about the REVERIE VG evoking better user satisfaction than Edu-Simulation (see **H2** in Section IV), at least related to how students perceived the VE. Curiously, their positive perceptions did not translate to enhanced spatial knowledge of the virtual space in REVERIE VG.

Additional ANOVA comparisons investigating the influence of the order of systems and task variation variables did not show any significant effects on any of the CoA questionnaire items. This finding is evidence to reject the third hypothesis of the study (see **H3** in Section IV), as students did not perceive any of the educational activities as "better" on REVERIE VG compared to Edu-Simulation. However, there was a significant main effect of tasks on the following Edu-Simulation questionnaire items:

- Item 1 (*"The educational activity in Edu-Simulation was simple"*) (F (1,34) = 4.484; p < .05);
- Item 6 (*"Edu-Simulation was enjoyable and easy to use"*) (F (1, 34) = 20.014; p< .001).

The descriptive statistics for item 1 (see Table 9) reveals that students perceived the individual task as easier to complete (mean Individual = 4.61) than the group task (mean Group = 3.77). Students most likely found the group task more complex because of the asynchronous text chat they had to use to communicate with their peers. Then, the descriptive statistics for item 6 reveal that students thought that Edu-Simulation was more enjoyable and easier-to-use when completing the individual activity (mean Individual = 5.61) than when experiencing the group activity (mean Group = 3.77). Provided students thought that the individual activity was simpler to the group activity it can be assumed that they enjoyed using Edu-Simulation to complete it. Both findings provide the evidence to accept the hypothesis that Edu-Simulation is a better platform and more enjoyable for the individual tasks (see **H4** in section IV).

TABLE 9: EDU-SIMULATION ITEMS WITH SIGNIFICANT MAIN EFFECTS OF TYPE OF TASK

Item	Group	Std. Deviation	Individual	Std. Deviation	Sig.
Item 1	3.77	1.11	4.61	1.24	.042
Item 6	3.77	1.47	5.61	0.91	.000

5) Virtual Representations Questionnaire (Common to both teachers and students)

Teachers gave average ratings for most of the virtual representation qualities of REVERIE VG. A possible explanation for the low ratings in the user VH quality is the use of spatial audio feature.

TABLE 10: TEACHERS MEAN RATINGS OF REVERIE VG VIRTUAL QUALITIES

Qualities	REVERIE VG	Std. Deviation
User VH	3.96	1.67
Communication between VHs	4.27	1.53
Feedback Mechanisms	4.40	1.42

The spatial audio was most likely perceived by teachers as an obstacle to their communication with students and hence, as an unnecessary feature for the gallery. Additional ANOVA comparisons for each questionnaire item did not return a significant main effect.

Students did not rate the virtual representation qualities of REVERIE VG significantly differently from their teachers.

TABLE 11: STUDENTS MEAN RATINGS OF REVERIE VG VIRTUAL QUALITIES

Qualities	REVERIE VG	Std. Deviation
User VH	4.24	1.77
Other Users VHs	4.39	1.66
Feedback Mechanisms	4.43	1.57

The average rating for the user VH quality shows that students perceived available modalities of communication in REVERIE VG (VHs and spatial audio) in a more positive light than their teachers. However, these ratings also show that students thought that more work was needed to improve these modalities further.

Additional ANOVA comparisons for students showed a significant main effect for task variation on the following questionnaire items:

- Item 9 (*"I found it easy to navigate my VH in the world using the available options"*) ($F(1, 34) = 4.361$; $p < .05$);
- Item 21 (*"It was easy to respond naturally (e.g., with appropriate emotions) during my interactions with other participants"*) ($F(1, 34) = 6.131$; $p<.05$).

Descriptive statistics show that students felt that it was easier to navigate in the virtual gallery when completed the group task (mean Group = 4.89) than the individual task (mean Individual = 4.0). A possible explanation is that in the group task students had to follow the group leader in locating an artefact in the VE, while in the individual task they had to complete this task on their own. Students also thought that it was easier to respond naturally to other users while completing the group task (mean group = 4.38) than the individual task (mean individual = 3.0). Students may have felt that additional communication modalities are required to properly respond in one-to-one communication scenarios, and the available modalities are sufficient for group communication.

TABLE 12: VIRTUAL QUALITIES ITEMS WITH SIGNIFICANT MAIN EFFECTS OF TYPE OF TASK

Items	Group	Std. Deviation	Individual	Std. Deviation	Sig
9	4.89	1.28	4.0	1.10	.044
21	4.38	1.88	3.0	1.45	.018

C. Post-Task Group Interviews

During the interviews teachers and students suggested various comments about the prototypes. Below, selected comments are presented which provide deeper insights into user performance and subjective experience.

1) Students' spatial knowledge

Students thought it is essential to interact with the displayed objects (e.g., to select and closely examine an object) to remain engaged and motivated with educational activities in REVERIE VG.

2) Students' subjective experiences

Students mentioned that it was easier to realise the scale of the objects in REVERIE VG compared to Edu-Simulation.

Students also mentioned that gathering in front of an object to listen to a student presenting further engaged them with the educational activity.

Students preferred REVERIE VG for completing gamified educational tasks compared to Edu-Simulation.

3) Teachers' subjective experiences

Teachers mentioned that REVERIE VG was instantly engaging, but they had issues related to control and communication with students.

Teachers felt that Edu-Simulation might not be appropriate for tasks to be completed during class time. The platform may be more suitable for tasks outside the classroom (e.g., in a collaborative research project).

Overall, teachers felt that the systems complement each other. For this reason, they recommended combining the best features of the prototypes into a hybrid platform that should provide engaging VEs to navigate and explore, supported by customisable VHs for students and teachers. Supporting textual, as well as speech communication, and allowing keeping a dialogue log. Furthermore, allowing the creation of groups, supporting public and private communication between them and allowing users with different roles to access groups' private communication. Finally, allowing accessing information and documents.

VI. CONCLUSIONS AND FUTURE WORK

In this study, the potential impact of multimodal CVE and gamification on the user's spatial knowledge was studied. The analysis of the objective data shows that the use of a multimodal CVE did not benefit the students' spatial performance. However, the subjective data shows that it was easier for students to build a mental map of the VE on REVERIE VG compared to Edu-Simulation. It also shows that it was easier to use the available input modalities on REVERIE VG than on Edu-Simulation. Students also reported having overall more positive experiences with the educational tasks on REVERIE VG. The task variation (individual or group) did not have any impact on how they perceived the cognitive accessibility and usability of REVERIE VG. It had, however, an impact on how participants perceived the spontaneity of their responses with other participants. It also had an impact on how students perceived how easy it was to navigate in the VE. Students thought it was easier to respond naturally to other participants in groups than individually. In contrast to their students, teachers perceived the quality of Edu-Simulation interface better than REVERIE VG. There were no other differences in the way they perceived the two systems. This could be one of the reasons teachers suggested combining the best features of the two systems into a hybrid system. Overall, it is safe to conclude that when the desired outcome of the interaction is enhanced spatial performance using a multimodal CVE is not detrimental, but also not beneficial.

The REVERIE framework does not enable building cloud-based CVEs applications. Although the prototype was taken to schools it was not evaluated during the actual class time. The context of the study may strongly influence the evaluation metrics (either positive or negative) and provide deeper user insights.

A possible avenue for future work is to merge the two systems in a hybrid system. A hybrid platform can have a significant positive impact on the user's experiences and their ability to retain spatial knowledge from a VE. Finally, the commercialisation of VR headsets (e.g., Oculus Rift) can offer a significant advantage for REVERIE virtual worlds. HMD users can immerse deeper into VEs which can significantly impact their experiences and spatial knowledge they retain from the environment. As such studies are scarce, we believe that this is a suitable area where effort should be directed in future development and evaluation work.

ACKNOWLEDGEMENTS

The research that led to this paper was supported by ………………………...

REFERENCES

[1] M. Garrett, "Sub space : enhancing the spatial awareness of trainee submariners using 3D simulation environments," Faculty of Education and Arts, Edith Cowan University, 2007.

[2] D. Waller, E. Hunt, and D. Knapp, "The Transfer of Spatial Knowledge in Virtual Environment Training", Presence, vol. 7, no. 2, pp. 129-143, 1998.

[3] B. G. Witmer, J. H. Bailey, B. W. Knerr, and K. C. Parsons, "Virtual spaces and real world places: Transfer of route knowledge". 1996, pp. 413-428.

[4] T. S. Hussain, B. Roberts, C. Bowers, J. A. Cannon-Bowers, E. S. Menaker, S. L. Coleman, C. Murphy, K. Pounds, A. Koenig, R. Wainess, and J. Lee, "Designing and Developing Effective Training Games for the US Navy," in Proceedings of the Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC), Orlando, USA, November 30 - December 3, 2009.

[5] S. E. Kober, G. Wood, D. Hofer, W. Kreuzig, M. Kiefer, and C. Neuper, "Virtual reality in neurologic rehabilitation of spatial disorientation," Journal of NeuroEngineering and Rehabilitation, vol. 10, no. 1, 2013, p. 17,.

[6] R. Molina-Carmona, M. Luisa Pertegal-Felices, A. Jimeno-Morenilla, and H. Mora, "Virtual Reality Learning Activities for Multimedia Students to Enhance Spatial Ability". 2018, p. 1074.

[7] I. Doumanis, D. Economou, G. R. Sim, and S. Porter, The impact of multimodal collaborative virtual environments on learning: A gamified online debate, Computers & Education, vol. 130, September 2019, pp. 121-138 (available online September 2018).

[8] F. Xu, D. Buhalis, and J. Weber, "Serious games and the gamification of tourism," Tourism Management, vol. 60, 2017, pp. 244-256.

[9] G. Burdea, P. Richard, and P. Coiffet, "Multimodal virtual reality: Input - output devices, system integration, and human factors," International Journal of Human-Computer Interaction, vol. 8, no. 1, 1996, pp. 5-24.

[10] D. Economou, I. Doumanis, V. Bouki, F. Pedersen, M. Mentzelopoulos, and N. Georgalas, "Edu-simulation: A serious games platform designed to engage and motivate students," in 2015 International Conference on Interactive Mobile Communication Technologies and Learning (IMCL), 2015, pp. 244-248.

[11] P. Fechteler et al., "A framework for realistic 3D tele-immersion," ACM International Conference Proceeding Series, 10.1145/2466715.2466718..

[12] J. Wall et al., "REVERIE: Natural human interaction in virtual immersive environments," in 2014 IEEE International Conference on Image Processing (ICIP), 2014, pp. 2165-2167.

[13] T. Garling, A.Book, and E.Lindberg, "The acquisition and use of an internal represenation of the spatial layout of the enviroment during locomotion". Association for the Study of Man-Environment Relations, 1979.

[14] R. G. Golledge and R. J. Stimson, "Spatial Behavior: A Geographic Perspective". Guilford Press, 1996.

[15] M. Billinghurst and S. Weghorst, "The use of sketch maps to measure cognitive maps of virtual environments", *Proceedings Virtual Reality Annual International Symposium '95*, Research Triangle Park, NC, USA, 1995, pp. 40-47.

[16] H. Bai, G. Richard, and L. Daudet, "Geometric-based reverberator using acoustic rendering networks," in 2015 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA), 2015, pp. 1-5.

[17] K. C. Apostolakis and P. Daras, "RAAT - The reverie avatar authoring tool," in 2013 18th International Conference on Digital Signal Processing (DSP), 2013, pp. 1-6.

[18] J. Nielsen. (2012, 8 August). Usability 101: Introduction to Usability. Available: https://goo.gl/m3mDbF

[19] L. Seeman and M. Cooper, "Cognitive Accessibility User Research," Available: https://www.w3.org/TR/coga-user-research/

[20] D. Norman, "The design of everyday things: Revised and expanded edition". Basic Books (AZ), 2013.

[21] J. R. Lewis, "Psychometric Evaluation of the PSSUQ Using Data from Five Years of Usability Studies," International Journal of Human–Computer Interaction, vol. 14, no. 3-4, pp. 463-488, 2002/09/01 2002.

[22] R. Adams, "Decision and stress: cognition and e-accessibility in the information workplace," Univers. Access Inf. Soc., vol. 5, no. 4, pp. 363-379, 2007.