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Review Article

Effects of a virtual reality game on learning performances and motivation: example of Nanoviewer in the field of energy storage

Emilie Loup-Escande[1*], Simon Herbulot[1], Alain Ngandjong[2,3], Romain Lelong[4], Guillaume Loup[5] and Alejandro A. Franco[2,3,6,7*]

[1]*CRP-CPO EA7273, Université de Picardie Jules Verne, 1 chemin du Thil, 80025 Amiens Cedex 1, France*
[2]*LRCS UMR 7314, Université de Picardie Jules Verne, HUB de l'Energie, 15 Rue Baudelocque 80039 Amiens cedex 1, France*
[3]*Réseau sur le Stockage Electrochimique de l'Energie (RS2E), CNRS FR 3459, HUB de l'Energie, 15 Rue Baudelocque, 80039 Amiens, France*
[4]*Société REVIATECH, parc technologique des rives de l'Oise, rue les rives de l'Oise, 60280 Venette, France*
[5]*IBISC EA4526, Univ Evry - Université Paris Saclay, 91020 Evry, France*
[6]*ALISTORE-European Research Institute, CNRS FR 3104, HUB de l'Energie, 15 Rue Baudelocque, 80039 Amiens, France*
[7]*Institut Universitaire de France, 103 Boulevard Saint Michel, 75005 Paris, France*

***Correspondence to:** Emilie Loup-Escande, CRP-CPO EA7273, Université de Picardie Jules Verne, 1 chemin du Thil, 80025 Amiens Cedex 1, France, Tel: Tel.: +33 (0)3 22 82 89 12; Email: emilie.loup-escande@u-picardie.fr

Alejandro A. Franco, LRCS UMR 7314, Université de Picardie Jules Verne, HUB de l'Energie, 15 Rue Baudelocque 80039 Amiens cedex 1, France, Tel : +33 (0)3 22 82 53 36; Email : alejandro.franco@u-picardie.fr

Abstract

Many studies have been conducted in the field of Virtual Reality (VR) for chemistry learning. However, no studies have been performed in the field of electrochemical energy storage, only few studies in other fields involve immersive VR devices and those have been conducted in classroom (*i.e.*, uncontrolled environment). To fill these gaps, our study investigates the effects of VR in terms of performance learning and motivation in an experimental context that provides data from a controlled environment. Results showed that participants using VR were more efficient and effective than participants not using VR; no significant difference was observed between the two groups for learning outcomes; intrinsic motivation and identified regulation were higher for VR participants than non-VR participants.

Keywords: Virtual Reality, Learning, Electrochemical Energy Storage, Performances, Motivation.

Introduction

Virtual reality (VR) refers to a three-dimensional virtual environment (Milgram & Kishino, 1994) where users can be immerged into and interact with (Fuchs et al., 2006), by using specific devices (Muhanna, 2015). Many studies have been conducted in the field of VR for learning over the past decade (Freina & Ott, 2015). These studies have explored its role in a variety of educational settings, particularly in elementary schools (Adamo-Villani & Wilbur, 2008), junior high schools (Schrader & Bastiaens, 2012) and higher education institutions (Van der Land et al., 2013; Tarng et al., 2019), where VR has been used to create new forms of learning. In their state of the art, Mikropoulos and Natsis (2011) have listed 40 out of 53 empirical studies referred to science, technology and mathematics. Among them, most studies involve desktop-VR displays (in chemistry, Dalgarno et al., 2009; Merchant et al., 2014). The majority of the reported studies investigated the educational added-value through the learning outcomes gained by VR and some studies focus on immersive VR (Limniou, Roberts & Papadopoulos, 2008; Parong & Mayer, 2018), whereas only few report on motivation (Loup et al., 2016). Moreover, the few studies comparing VR and 2D representations have been conducted in the classroom (Jou & Wang, 2013; Lukman & Krajnc, 2012). Even if they are "ecological" and representative of the actual situation of use, these studies have not been conducted in a fully controlled environment limiting parasitic variables. A controlled environment is an environment in which only the device changes (3D animations on HTC Vive vs. printed 2D representations), the experimenter (the teacher or the scientist), the measurement tools (task, questionnaires, completion time and so on) as well as the conditions and the place in which the experiment is performed are identical in both groups.

The aim of the present study is to examine the effects of VR on learning performances and motivation. For that, we compared two groups: an experimental group constituted of participants who used VR after reading a printed document on lithium ion batteries to answer a printed questionnaire, and a control group composed of participants who only had access to the same printed document and questionnaire.

Related work

Virtual reality for learning

Virtual reality in the field of learning presents many potential interests for the learner (Burkhardt, 2003): the motivation to learn through the playful aspects associated with this technology, the realism to apprehend the real without risk and at a lower cost, the multiplicity of virtual "learning grounds", and finally the access to impossible forms of interaction and visualization in the physical world (e.g., examining a molecule on the scale of this molecule). This technology would be for the teacher, a way to solve some difficulties or misunderstandings related to the language and static of printed documents (specially to understand complex systems in their dynamics), to validate or invalidate learner responses as part of a more active pedagogy (Burkhardt, 2003).

For all these benefits, several mixed and virtual applications have recently been designed and experimented with. Frenoy et al., (2016) have implemented CalliSmart which is an interactive intelligent device that analyzes the gestural performance of learners and provides them with the most relevant feedback according to their activity. In biology, Parong and Mayer (2018) have compared the instructional effectiveness of immersive VR *versus* a desktop slideshow for college students. In the context of VirtualiTeach aiming at promoting the learning of science, technology, engineering and mathematics by highschool students, Loup-Escande et al., (2017) have evaluated Virtualkart. This application contained two activities: energy chain and power transmission. In the present study, participants performed the first activity, in which they had to associate five components of the kart's energy chain (i.e., battery, dimmer, engine, transmission belt and wheel) with their appropriate functions (i.e., supply, distribute, convert, transfer and act) so that the vehicle would run. The cost and difficulty of using a transmission electron microscope needed to see the transformation of the crystal structure led, Tarng et al. (2019) to experiment with VR to study a shape memory alloy.

Virtual reality and performance

In the field of VR for learning, previous studies have investigated performance through effectiveness, efficiency and learning outcomes.

Effectiveness and efficiency: According to the ISO 9241-11 norm, effectiveness refers to whether or not a goal is achieved, whereas efficiency refers to reaching the goal with the least effort or in the shortest time. Studies focused in VR for learning, often measure effectiveness through failure/success at the task, and efficiency by the time needed to achieve the task (Loup-Escande et al., 2017; Loup & Loup-Escande, 2018; Tcha-Tokey et al., 2018). For example, Loup-Escande et al., (2017) have showed that users were more successful in an interactive mechanics learning task using a zSpace in the stereoscopic condition. Other authors prefer to cross several methods to measure effectiveness and efficiency. For example, Tarng et al., (2019) used an achievement test based on multiple-choice questions, a satisfaction survey and observation records to obtain quantitative and qualitative data.

Learning outcomes: More recently, Merchant et al., (2014) conducted a meta-analysis on the effects of VR in learning, based on 67 studies carried out among elementary, middle- and high-school pupils and undergraduates. These authors included in their meta-analysis studies of simulations, games and virtual worlds. They observed that mixed approaches (i.e., VR combined to other methods) seemed to be more effective. Furthermore, the learning gain decreased with prolonged use of games, and learning performances were higher when participants played the games individually rather than in groups. In these studies, a knowledge questionnaire has been provided after the task to check the learning outcomes (e.g. Limniou et al., 2008; Loup-Escande et al., 2017). In chemistry education, Limniou et al., (2008) studied the educational benefits of an immersive VR device (named CAVE). For this, they presented to the same group of 14 students a 2D animation representing a chemical reaction at the atomic scale. Then, this same group was exposed to an animation presenting the same chemical reaction, but this time in the CAVE, with the possibility of moving the structure, to look at it in several different angles. After each presentation, the experimenters asked the students to complete a questionnaire on the visualized chemical reaction. The results showed that students using VR understood better the molecules' structure and their changes during a chemical reaction than students using 2D animations on a desktop-VR. Furthermore, the students were enthusiastic because they had the feeling that they were inside the chemical reactions. We can notice that similar VR tools and analysis efforts have never been reported in the field of energy storage, in relation to batteries, their materials and their operation principles (Franco, 2013).

Virtual reality and motivation

Studies have shown that the use of the current VR improves student motivation (Ryan, Rigby & Przybylski, 2006). In learning literature, motivation understood in the sense of Deci and Ryan (2007), can be classified in three categories:

- The intrinsic motivation, which appears when a person does an activity for his own pleasure, and finds this activity interesting and satisfying.
- Extrinsic motivation, which occurs when a person performs an activity according to an external consequence, for example the idea of obtaining a reward, or to escape punishment.
- In a state of amotivation, the person lacks the intention to act, intentionally. He/she thinks it will not give any result and feels incompetent.

Among recent studies, Loup et al., (2016) have investigated on the impact of a VR prototype named REARTH vs. usual devices in a classroom; results suggest that using the immersive and persistent prototype students were more engaged in learning. In these studies, motivation is often measured by a questionnaire like the Situational Motivation Scale (Guay, Vallerand & Blanchard, 2001).

Aims and hypotheses

Our objective was guided by two points: findings from the literature and real educational needs. Three main observations can be distilled from our remarks so far: 1) even if several studies investigated the educational added value through the learning outcomes gained by desktop-VR (Dalgarno et al., 2009; Merchant et al., 2014;), few involve immersive device (Tarng et al., 2019; Parong & Mayer, 2018); 2) VR seems to have a real interest in chemistry education (Freina & Ott, 2015); 3) if there have been studies in classroom, i.e. in an uncontrolled environment (Lukman & Krajnc, 2012; Koretsky, Kelly, & Gummer, 2011), the effects of VR have so far not been studied both in terms of performance learning and motivation in an experimental context that would provide data from a controlled environment. Moreover, a chemistry professor found that several students had difficulty understanding the mesoscopic structures representing battery composite electrodes. VR, allowing to visualize and manipulate a structure on the real scale and in 3D contrary to 2D printed representations, was an interesting solution to improve understanding and students' motivation.

The aim of the present study was consequently to examine the effects of VR (i.e., 3D animation on HTC Vive) on learning performances and motivation. After reading a lesson on lithium ion batteries, participants performed a task in which they had to count and to give an estimation of the number of "large particles" (i.e., representing the active material) present in a structure representing a lithium-ion battery electrode (with VR for the experimental group vs. with a printed 2D representations for the control group), and they had to complete a knowledge questionnaire.

The three metrics used to measure learning performances of users were effectiveness, efficiency and learning outcomes. In line with Limniou et al., (2009) and Loup-Escande et al., (2017), we hypothesized that the experimental group would be more effective, that is to say better at counting and giving an estimation of the number of "large particles", than the control group (Hypothesis 1). Concerning efficiency, we hypothesized that the experimental group would be more efficient, that is to say faster, than the control group (Hypothesis 2). In line with Limniou et al., (2009), we hypothesized that learning outcomes were better in the experimental group compared to the control group (Hypothesis 3).

The three metrics used to measure motivation by users were intrinsic motivation, extrinsic motivation and amotivation. The above-mentioned studies (e.g., Limniou et al., (2009) showed that intrinsic motivation is higher with VR than with the tradition lesson. We therefore hypothesized that the intrinsic motivation experienced in the experimental group would be greater than in the control group (Hypothesis 4). Loup et al. (2016) have shown that there was no difference in the scores between VR and traditional lesson concerning the extrinsic motivation and the amotivation. So, we also hypothesized that the extrinsic motivation experienced in the experimental group mode is similar in the control group (Hypothesis 5), and that the amotivation in the experimental group is similar in the control group (Hypothesis 6).

Methods

Participants

Thirty-eight participants (22 women and 16 men) who had volunteered to take part in this study were assigned to one of the two conditions (lesson + VR *vs.* lesson + 2D printed). Two groups were constituted: 19 in lesson + VR condition (*i.e.*, experimental group) and 19 in lesson + 2D printed condition (*i.e.*, control group). Participants were students in psychology, aged 20-26 ($M = 21.56$, $SD = 1.59$). These groups were homogeneous in terms of subjects' familiarity with VR (control group: $M = 4.97$, $SD = 6.80$; experimental group: $M = 4.74$, $SD = 1.10$; $t(36) = .80$, $p = .43$, two-tailed. They were homogeneous concerning knowledge in chemistry (control group: $M = 1.22$, $SD = 0.50$; experimental group: $M = 0.96$, $SD = 0.59$; $t(36) = 1.43$, $p = .16$, two-tailed.

Materials and measures

***Nanoviewer* on HTC Vive:** The application used in this study was *Nanoviewer*, an immersive environment jointly developed by LRCS and Reviatech that allows a user to manipulate mesoscopic structures representing battery composite electrodes (Figure 1). Such structures are generated by employing a model supported on the Coarse Grained Molecular Dynamics approach, used to simulate the lithium ion battery electrode fabrication (Ngandjong et al., 2017). Large particles represent the active material (where lithium intercalate/de-intercalate upon lithium ion battery cycling) and small particles represent carbon-binder domains (with the role of ensuring good electronic percolation between the composite electrode and good adhesion between active material particles). For the experience reported in this paper, we choose a specific structure representing a composite electrode with mass composition of 90% active material and 10 % of carbon-binder particles. The size of the simulated composite electrode is of 50 x 50 x 50 µm. We identified several possible interactions with the structure:

- enlarge the structure, using a movement of arm spacing, with both handles, to be able to "dive" inside the structure,
- shrink the structure, using a movement of arm spacing, always with both handles,
- using a single handle, grab the structure to rotate it, move it in space, move it away or move it closer together.

The VR device used to interact with *Nanoviewer* was an HTC Vive head-mounted display that allow easy interaction with controllers (Figure 2).

Lesson on lithium-ion battery: This course, developed with two of the authors (one of which is a university professor and researcher in the field of lithium-ion batteries) was intended to be accessible to novices (our sample is composed of students in psychology). It described the operation and components of a lithium-ion battery, and a description of its electrodes. The task to be performed by the participants concerned these electrodes.

Task: After reading a lesson on lithium-ion battery, participants performed a task in which they had to count and to give an estimation of the number of "large particles" (i.e., representing the active material) present in a structure representing a lithium-ion battery electrode (Figure 3), with VR for the experimental group vs. with a printed 2D representation for the control group. It was a parallelepiped shaped structure containing 27 "large particles" and many small particles (carbon).

Participants in the experimental group were to perform this task using *Nanoviewer*, while the participants from the control group performed the task in 2D, using sheets on which the 6 faces of the structure were represented, in an exercise similar to mental rotation (Figure 4).

Task performances were identified through the success or failure measure and task completion time. Concerning the success/failure

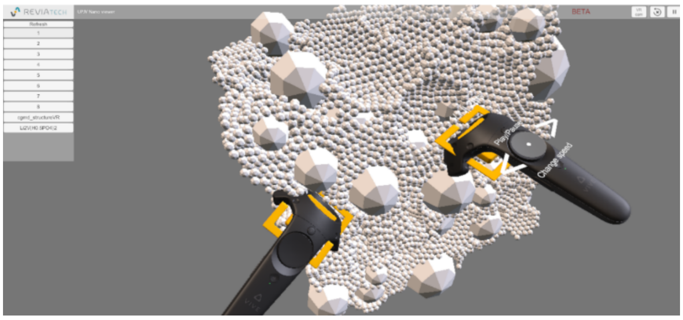

Figure 1. *Nanoviewer* software allowing to visualize in immersive conditions a virtual structure representing a lithium ion battery composite electrode.

Figure 2. HTC Vive device.

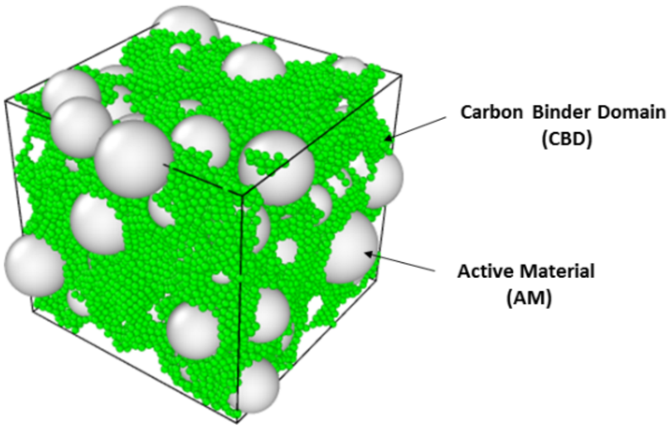

Figure 3. A lithium ion battery composite electrode.

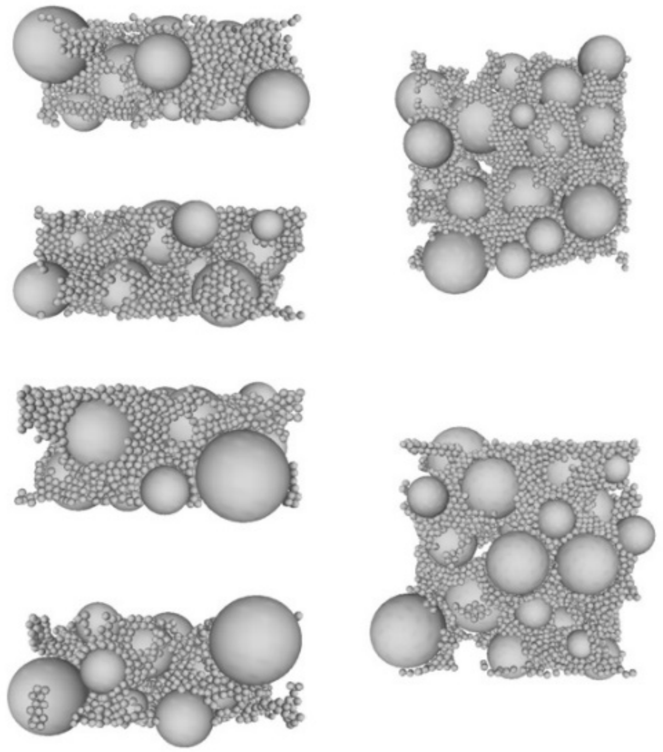

Figure 4. Printed 2D graphs of a structure representing, from different viewpoints, a lithium ion battery composite electrode.

measure, participants were deemed to have successfully completed the task if they correctly estimated the number of large particles.

Questionnaires: Participants were asked to answer four questionnaires: one before, and the remaining three after performing the task.

The questionnaire filled in before the task contained 13 questions: four demographic items (age, gender, laterality, occupation), five items about familiarity with technologies and VR, adapted from the Likert scales-based questionnaire devised by Tcha-Tokey et al., (2018) (e.g., "I have knowledge in virtual reality"), and four items on familiarity with chemistry and lithium ion batteries (e.g., "How do you qualify your knowledge in chemistry?").

The SIMS questionnaire is used to measure motivation (Guay et al., 2001). The French version contained 16 items rated on 7-point Likert-like scales scored from 1 to 7 such as suggested by Blanchard and Frasson (2007): four intrinsic motivation items, four identified regulation items, four external regulation items and four amotivation items.

The answer questionnaire is used to collect the users' answer after completing the task (i.e., the number of large particles identified).

The learning questionnaire is used to collect information on participants' understanding through nine items. These items were questions on knowledge on the lesson concerning the lithium ion battery provided to the students (e.g., "Among the two structures presented, which one has the largest porosity?"). We assigned a total score of 9 points to each participant (for each question, 1 point per correct answer, 0 point for a wrong answer).

Procedure

Once participants had answered the pre-task questionnaire (personal details), the experimenter explained the aims and presented the peripherals (experimental group) or traditional support (control group) to be used and the actions to be undertaken in order to count the number of active material particles in either VR or 2D-printed representation. A lesson on lithium ion batteries has been provided to the participants on a paper support. We have clarified that they had 10 minutes to read and retain as much information as possible. Then, participants performed the task. Finally, they completed the other two questionnaires (motivation, knowledge).

Results

We ran a test of normality (i.e., Shapiro Wilk test). The data was analyzed using the nonparametric Mann-Whitney U test when the Shapiro Wilk test indicated a significant result ($p < 0.05$), while a Student's t test was used when the Shapiro Wilk test indicated a non-significant difference ($p > 0.05$).

Effects of virtual reality on effectiveness, efficiency and learning outcomes

An independent-samples *t* test showed a non-significant difference for effectiveness between experimental group ($M = 26.21$, $SD = 4.54$) and control group ($M = 30.84$, $SD = 18.23$). However, we observe that the responses done by the experimental group are closer to the correct answer (i.e., 27 large particles) compared to the control group. Participants using VR give answers approaching the correct answer, while those using printed 2D representations provide more distant answers. This suggests that VR would allow participants to be more effective than with 2D representations. A Mann-Whitney *U* test revealed a significant difference in efficiency between experimental group ($M = 56.42$, $SD = 30.26$) and control group ($M = 315.37$, $SD = 210.11$), U=6, p<.000. Participants using 3D animations on HTC Vive are faster in performing the task than those using printed 2D representations. An independent-samples *t* test showed a non-significant difference for learning outcomes between experimental group and control group. Participants using VR scored the same on the learning questionnaire as those who did not use it. Also, VR does not seem to affect the knowledge finally acquired.

Effects of virtual reality on motivation

A Mann Whitney *U* test revealed a significant difference in intrinsic motivation between experimental group ($M = 6.26$, $SD = 1.17$) and control group ($M = 4.17$, $SD = 1.64$), U=67.50, p=.001. Participants using VR take more pleasure and find the pedagogical activity more interesting than participants using printed 2D representations.

Concerning extrinsic motivation, no significant differences were observed for extern regulation, while an independent-samples *t* test showed a significant difference for identified regulation between experimental group ($M = 4.95$, $SD = 1.39$) and control group ($M = 3.79$, $SD = 1.33$), $t(36) = -2.62$, $p = .01$, two-tailed. Participants using 3D animations on HTC Vive think that the task is useful for them, unlike participants using printed 2D representations.

A Mann Whitney *U* test revealed a non-significant difference in amotivation between experimental group and control group. So, the intention to perform the task is equivalent between the two groups.

Discussion

Our first hypothesis, namely that the experimental group would be more effective, that is to say better at counting and giving an estimation of the number of active material particles, than the control group, was partially validated. Even if an independent-samples t test showed a non-significant difference for effectiveness between the two groups, we observe that the responses made by the participants using VR (M = 26.21 particles, SD = 4.54 particles) are closer to the correct answer (i.e., 27 large particles) compared to the participant using printed 2D representations (M = 30.84 particles, SD = 18.23 particles). This result is consistent with the findings of previous studies (Merchant et al., 2014) and shows that VR allows students to better manipulate and visualize the mesoscopic structures representing battery composite electrodes.

Our second hypothesis, that the experimental group would be more efficient, that is to say faster than the control group, was entirely validated. In line with Ryan, Rigby & Przybylski (2006), we observed that VR improves completion times related to the task, compared to the printed 2D representations.

Our third hypothesis, that learning outcomes were better in the experimental group compared to the control group, was not validated. Contrary to Tarng et al. (2019), we observed that scores of learning outcomes in experimental and control groups were nearly identical. However, this is consistent with Parong and Mayer (2018), who have showed that students who viewed the slideshow performed significantly better on the posttest than the VR group. It may be explained by the fact that our participants were not chemists or physicists and did not have enough basis to assimilate the content of the lesson in both groups.

Our fourth hypothesis, that the intrinsic motivation experienced in the experimental group would be greater than in the control group, was validated. Indeed, this result is consistent with the findings of previous studies claiming that VR would increase the motivation to learn due to the playful aspects (Burkhardt, 2003).

Our fifth hypothesis, that the extrinsic motivation experienced in the experimental group mode is similar to the control group one, was validated in relation to only one of the two extrinsic motivation metrics. Even though previous studies showed that there was no difference in the scores between VR and traditional lessons concerning the extrinsic motivation (Loup et al., 2016), our results indicate that this is correct only for the external regulation which occurs when a person performs a task to satisfy external demand, or for the purpose of receiving a reward or avoiding constraints (Tcha-Tokey et al., 2018). However, the identified regulation is higher with VR. This might be explained because the identified regulation appears when an individual carries out a task because it brings him/her something, even if it is not interesting (Blanchard & Frasson, 2007).

Our sixth hypothesis, that the amotivation in the experimental group is similar in the control group, was validated. This suggests that the intention to perform the task is equivalent between the two groups. This result is consistent with the findings of previous studies (Loup et al., 2016).

Conclusion

The present study yielded knowledge about the effects of VR on learning performance and motivation. Participants performed a task in which they had to count and to give an estimation of the number of “large particles” (i.e., representing the active material) present in a mesostructure representing a lithium ion battery composite electrode of 50 x 50 x 50 μm^3 (with VR for the experimental group vs. with 2D printed representation for the control group). It was a parallelepiped shaped mesostructure containing 27 active material particles and many small particles (representing the carbon/binder domains in the electrode). To compare these two groups, we collected three measures of performances in terms of effectiveness, efficiency and learning outcomes, and three measures of motivation: intrinsic motivation, extrinsic motivation and amotivation. Results showed that VR allows participants better efficiency and better effectiveness than participants of the control group. Concerning the learning outcomes, no significant difference was observed between the two groups. In terms of motivation, VR created a higher intrinsic motivation and a higher identified regulation compared the control group.

One limitation of our study is that the only qualitative data we collected were responses to questionnaires. It would probably have been appropriate to conduct videotape self-confrontations. This would have allowed us to collect further explanatory data on the difficulties perceived by participants during the task completion. This can be inserted into the data collection protocol for future empirical studies.

A second limitation of our study was that it featured a very specific learning task. Only by conducting complementary studies can we find out whether these results can be generalized to other learning tasks. Furthermore, the task was administered only once, and our results therefore do not provide any information about how users’ experience change over time. For example, the positive effects of VR on motivation may have been due to the novelty effect. Longitudinal studies are needed to investigate these measures over the long term ((Mikropoulos & Natsis, 2011; Merchant et al., 2014; Khan, Johnston & Ophoff, 2019) for similar comments). In the close future, we plan to perform similar studies with other VR serious games developed at UPJV, also dealing with rechargeable batteries.

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