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Collaborative science learning in an immersive flight simulation

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ABSTRACT

This mixed methods study examined the effect of Astronaut Challenge, an immersive, flight-simulation-based learning program, on the collaborative learning process and science knowledge development of high-school students. The study findings suggested that simulation-based collaborative learning activities significantly promoted students' scientific understanding about the dynamics of the space flight system. The knowledge test and STEM attitudes survey results did not indicate a significant difference between two immersive contexts of the simulation (exclusive-space flight simulation versus classroom flight simulation) in influencing the learning outcomes. Qualitative findings suggested that the higher level of the sensory immersion in a simulation-based learning environment may foster task engagement and procedural practice but not collaborative conceptual processing.

1. Introduction

Immersion is a salient feature of the simulation-based learning environment. According to Dede (2009), immersion refers to "the subjective impression that one is participating in a comprehensive, realistic experience" (p. 66). It can be interpreted as a psychological experience that one perceives regarding how much s/he is attached to a learning environment, which can be provided via an active and dynamic interaction between the learner and their environment, sensory information in the 3D digital space, and authentic scenarios or tasks that tap into the learner's life experiences (Baños et al., 2004; De Freitas, Rebolledo-Mendez, Liarokapis, Magoulas, & Poulovassilis, 2010; Dede, 2009). Studies have shown that immersive digital simulations, delivered via a computer-assisted simulator or a virtual reality, can enhance education by allowing multiple perspectives, situated learning, and transfer (e.g., Dunleavy, Dede, & Mitchell, 2009; Freitas & Neumann, 2009; Hansen, 2008). However, research on the effects of immersion on collaborative learning processes is still limited and the result is inconclusive. Research is also needed on the learning benefits and preferences that different levels of immersion in the digital space of a simulation cultivate for a diverse learner group, which guides the instructional arrangement of interactive media in a simulation-based collaborative learning environment.

Prior research suggested that immersive, participatory simulation is an emerging and a prominent learning tool to help learners understand a complex, dynamic science system (Barab & Dede, 2007; Colella, 2000). Learning about complex

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systems is difficult because complex systems aggregate multiple components that interact with each other in multiple levels (Hmelo-Silver & Azevedo, 2006). Sterman (1994) argued that approaches to learning about complex dynamic systems require tools to frame issues and elicit/create an iterative feedback-based learning cycle, and methods to improve group or team processes that will overcome defensive routines for individuals and sharpen their scientific reasoning skills. Based on such a perspective, it is warranted to examine the capabilities of digital immersive simulations in promoting collaborative learning and hence understanding about a complex, science system (such as the engineering system of a space flight).

Therefore, in this study we examined the design and effect of an immersive, simulation-based science learning program on the collaborative learning process and science knowledge development of high-school students. The major research question are: (a) What is the impact of a space flight simulation program on high school students' collaborative learning processes, their science knowledge, and positive disposition development? (b) Is there a differential effect of the immersive contexts of this simulation-based learning environment on the collaborative learning process and outcome?

2. Literature review

2.1. Immersive simulation and collaborative learning

It is asserted that simulation-based experiential and inquiry learning is a basic form of computer supported collaborative and constructive learning (O'Malley, 2012; Van Joolingen et al., 2005). Immersive simulations, in addition, will extend the computer-supported simulation from the computer screen to a surrounding microworld in which participants collaboratively role play, experience, and explore the dynamics of the simulated system (Colella, 2000). It is expected that immersive simulation will create a context or *space* within which participants can experiment with concepts as “an abstraction” from a sensory-motor experience (Pufall, 1988, p. 29). A potential benefit of immersive simulation is to stimulate intellectual curiosity by enabling learning interactions in real, physical space, thus engaging them in deep reasoning about the underlying structure of the simulation (Klopfer, Yoon, & Perry, 2005; Roschelle, 2003). It is also advocated that artifacts in an immersive simulation can act as shared representations and hence an effective representational tool to facilitate collaborative knowledge construction (Lin, Duh, Li, Wang, & Tsai, 2013).

On the other hand, empirical research examining immersive simulation and collaborative learning is limited. In a qualitative study, Colella (2000) examined a collaborative, participatory simulation of disease transmission in which students, via wearable computing, role-played agents conveying epidemic viruses in a life-sized microworld. She reported that learners displayed a robust and persistent level of immersion during the simulation activity. She also found that integrating the direct experience of a scientific phenomenon into the students' interpersonal space had enabled students to develop scientific inquiry skills, such as problem identification, hypotheses construction, and experimental design. Leemkuil, de Jong, de Hoong, and Christoph (2003) conducted a formative evaluation of a web-based, collaborative simulation game focusing on knowledge management (KM). Learners role-play in group as members of a virtual KM team to solve KM problems in a business, via both asynchronous and synchronous online communication tools. The study reported that participants' awareness of presence and peers' activities (called ‘workspace awareness’) mediated the collaborative learning process in the simulation. In a recent mixed-method study, Lin et al. (2013) compared the effectiveness of a mobile, collaborative augmented-reality (AR) simulation with a traditional 2D simulation in assisting task-oriented, physics knowledge construction for students in dyads. They reported that the learners using the AR-supported immersive simulation showed significantly better learning achievements, including knowledge test performance and the frequency of knowledge construction behaviors, than those learning with the 2D simulation.

2.2. Role of immersion in simulation-based learning

According to Murray (1997), immersion is a participatory activity associated with a psychological experience of being transported to an elaborately simulated place. Dede (2009) synthesized the literature and reported that immersion draws on sensory, actional, and symbolic facets (p. 66). Sensory immersion refers to the replication of the sensory interfaces of a three-dimensional space (e.g., audio, visual, and haptic experience). Actional immersion involves the engagement of the participants in simulated actions. Symbolic immersion triggers psychological associations (e.g., stress and fear) via the content of an experience. The salient factor that creates those three types of immersion in simulation is fidelity – the extent to which the simulation emulates the real world (Hays & Singer, 1989, 2012). Correspondingly, fidelity comprises physical, functional, and psychological facets. Physical fidelity refers to the degree to which the visual displays, audio, and instrument operation looks, sounds, and feels like the real operational environment; functional fidelity is the degree to which the tasks and interactions executed by the learners emulate the real operation; and psychological fidelity is the degree to which the simulation replicates psychological experiences in the real-world environment (Alexander, Brunyé, Sidman, & Weil, 2005; Hays & Singer, 2012).

Prior research on the simulations for learning suggested that an immersive work space crafted by a high fidelity simulation will enable learners to simultaneously process both 2D and 3D information (Febretti et al., 2013) and to better engage in inquiry learning through multiple perspectives (Dede, 2009). It is argued that immersion and fidelity evoked via a *surrounding* context, especially that replicates the interactivity and the psychological experience, will improve learning transfer from the simulation to the real world (Alexander et al., 2005). Furthermore, the theory of identical elements proposed that effective transfer between simulated and real environments occurs only when the simulated and real tasks have similar logical or deep structures rather than common surface elements (Chase & Ericsson, 1982; Lehman, Lempert, & Nisbett, 1988; Thorndike, 2013). A corresponding conjecture is that higher levels of physical/sensory fidelity is not as beneficial as that of functional fidelity in simulation-based learning, especially for the learning of abstract concepts.

Empirical studies of immersive and high-fidelity simulations typically focused on health, media arts, or environmental education for postsecondary students (Cook et al., 2013; Hew & Cheung, 2010; Issenberg, Mcgaghie, Petrusa, Lee Gordon, & Scalese, 2005). They aimed to evaluate the simulation's learning effectiveness rather than the immersion design features or the comparative effectiveness of varied immersive contexts. In a recent review of 24 studies contrasting high-fidelity simulations (HFS) versus low-fidelity simulations (LFS) for learning, Norman, Dore, and Grierson (2012) reported that both HFS and LFS learning resulted in improvements in performance in comparison with no-simulation control groups; yet almost all the studies reviewed showed no significant advantages of HFS over LFS, with only 1–2% average differences. On the other hand, some previous studies examining the comparative effectiveness of the levels of immersion and fidelity in simulation-based learning reported that high-immersion and high-fidelity learner groups scored higher than low-immersion and low-fidelity ones in the knowledge and skill transfer test (Brydges, Carnahan, Rose, Rose, & Dubrowski, 2010; Ragan, Sowndararajan, Kopper, & Bowman, 2010).

Drawing on the aforementioned theoretical foundations, this study investigated the educational value of using a 3D, immersive simulation to support collaborative learning of a complex science system. The study also experimented with two different immersive contexts (or immersion levels) to examine the role of immersion design in mediating the simulation-based learning processes and outcomes.

3. Methods

The study used a concurrent, mixed-method research approach (Clark & Creswell, 2011) to examine the immersive environment design and effect of a simulation-based science learning program. Student Astronaut Challenge, integrating a space flight simulation and a student manual on the basics of aerospace science, was the intervention program designed to promote collaborative, scientific inquiry learning.

3.1. Participants

Twenty 9–10th graders were recruited from the General Earth Space Science classes of a local high school to participate in an after-school, Student Astronaut Challenge program. Among the program participants, 50% were girls, and 45% were learning disadvantaged (e.g., at-risk to not graduate) or had special learning needs (e.g., English language learning or medical accommodation). Participants were randomly assigned to two simulation conditions: exclusive-space flight simulation condition ($n = 10$, in two project teams) and classroom flight simulation condition ($n = 10$, in two project teams). The wait-list students from the same classes formed a control group ($n = 71$). The procedure, immersive simulation design, and simulation-based collaborative learning activities are outlined below.

3.2. Procedure, immersive simulation program, and collaborative learning activities

This current study lasted 6 weeks. At the beginning of the first week, all study participants received a pre-test on science knowledge and a pre-survey on their attitudes toward science, mathematics, and engineering and technology (STEM). They were then given the Astronaut Challenge student manual to study during their weekly earth space science class and on their own at their convenient time and space. Participants of two simulation conditions also trained on space flight procedure one hour a week after school, from week 1 to week 6. Classroom simulation participants trained on the laptop-based space flight simulation, whereas exclusive space simulation participants trained on a physical space flight simulation. At the end of the sixth week, all participants received a posttest on the science knowledge and the post-survey. Each simulation project team also received a 30-min, semi-structured group interview.

The space flight simulation encompasses the following components to provide the computer-generated immersion for the program participants:

- Orbiter space flight simulation: Based on the freeware space flight simulation Orbiter, a 3D flight simulation of the launch, flight, and landing of the Space Shuttle Atlantis was developed and used to enable simulated space shuttle operation and deliver sensory inputs/outputs.
- PowerPoint multi-function display presentations: PowerPoint presentations, pre-timed with the orbiter program to run concurrently, were used to simulate the data displays (known as multi-function displays) on the Space Shuttle. They were also used to enable the simulation of emergent situations and mission control of the space flight. Each crew member will have different control (computer) screen that display task-specific visual data to be interacted with.
- Shuttle switch control panels: Four switch control panel templates were used to simulate the location of switches or control systems that must be turned on and off by the Mission Commander and Pilot during the flight.
- Flight operational and emergency procedure checklists: Pre-flight, in-flight, landing, and emergency procedure checklists, taken and customized from the actual ones used by space shuttle astronauts, were included as job aides for flight operations and emergency managements during flight.

- *Exclusive* Space Flight Simulation versus *Classroom* Flight Simulation: In the Exclusive Space Flight Simulation, a regular RV truck was customized to simulate a realistic space flight simulation. The physical set up, including display monitors, seats for the flight crew members, communication devices, and control panels, tried to artificially recreate the exclusive environment of a space flight. In comparison, the Classroom Flight Simulation was set up in a regular school classroom. Four desk computers, one overhead monitor, one computer joystick, and two radio control panels, along with regular classroom desks and chairs, were used to clone the functional setting of the space flight simulation. It is speculated that the exclusive-space simulation presents a higher sensory immersion than the classroom simulation.

3.2.1. Simulation-based collaborative learning activities

In both simulation conditions, participants were assigned into five-person teams, with each team being heterogeneous in terms of gender, ethnicity, and prior knowledge level. Each team consisted of a mission commander, pilot, mission specialist, and one to two mission control personnel. The initial positions in the team were randomly assigned among team members and eventually these positions were rotated between the teammates, allowing everyone to try multiple areas of responsibility. The students in each team would then practice as a group flying the space flight simulation using the procedure and emergency situation checklists. In both simulation conditions, the same facilitator was present during all simulation sessions, who provided technical and content help as needed.

The flight operation involved normal operation controls (e.g., launching, flying, and landing) at first, and then problem solving in managing varied technical emergency situations. Successful operation of the space flight simulation requires all astronauts to work together effectively, practice their individual jobs, and be aware of the jobs and responsibilities of the rest of the crew. Communication and collaborative operations among team members are essential, and the strict control of who speaks or does at what time and to whom is critical. The communication varied in its purposes (e.g., advises, announcements, or requests on status information), and required all members to swiftly identify what their responsibilities are, who they want to speak to, and what they need to know or report. This relationship is especially important when emergencies occur, therefore consistent practice together is necessary for an effective team.

3.3. Data collection, instruments, and analyses

Data in this mixed methods study were collected via both quantitative knowledge test and qualitative infield observation and interview. The pre- and post-intervention science knowledge tests were developed by drawing on the test items used in the Astronaut Challenge program of previous years. The content validity of the tests was validated by school science teachers participating in the program. The Middle/High School (6–12th) S-STEM Survey (FIEI, 2012) was adopted to measure potential changes in students' confidence and efficacy in STEM subjects and their interest in STEM careers. The survey's validity and reliability (0.89–0.92) were examined and reported in prior research (FIEI, 2012; Unfried, Faber, Stanhope, & Wiebe, 2015). The S-STEM survey includes 37 five-point Likert scale items (Cronbach's $a = 0.92$ in this study) measuring students' attitudes toward science, mathematics, and engineering and technology, and 12 four-point scale items (Cronbach's $a = 0.84$ in this study) measuring students' interest in STEM careers.

Pre- and post-program knowledge tests were analyzed using descriptive and inferential statistics. Specifically, ANCOVA analyses were conducted to examine the potential impact of the simulation-based science learning program on participants' science knowledge test performance and attitudes toward STEM, with the pre-intervention test and survey results as covariates and the study condition (e.g., treatment vs control, and types of the simulation) as the between-subjects factor.

Participants' collaborative learning activities during program sessions were observed and video recorded. A semi-structured, focus group interview was then conducted with each project team after the program activities. Interviews, classroom observations, and video recordings were transcribed. The qualitative thematic analysis was descriptive in nature, while focusing on understanding when, how, why, and with whom a simulation-based collaborative learning event occurred. We conducted *categorical aggregation analysis* (Clark & Creswell, 2011) with the observed and recorded team activities, by coding the critical actions and instances of simulation-based collaborative learning and then classifying them into aggregations. Salient and frequently coded aggregations emerged as the themes. Peer debriefing were conducted among the two coders and member checking were performed with the participants during the interview process. Finally, we sought meaningful themes among the categories and synthesizing naturalistic conditions and consequences of the major themes. These themes were then consolidated with quantitative findings.

4. Findings

4.1. Impact of simulation-based science learning

An ANCOVA test was conducted to examine the effect of the simulation-based science learning program on the post-intervention knowledge test performance, with the pretest scores ($M_{tre} = 32.37$, $SD_{tre} = 11.24$; $M_{crl} = 31.97$, $SD_{crl} = 8.80$) as the covariate. The analysis indicated a significant difference between the treatment (simulation) group and the control (non-simulation) group, $F(1, 88) = 10.83$, $p = 0.001$, partial $\eta^2 = 0.11$. The test performance of the treatment group (simulation-based collaborative learning, $n = 20$, $M_{tre} = 57.94$, $SEM_{tre} = 3.40$) was significantly higher than that of the control group ($n = 71$, $M_{crl} = 45.34$, $SEM_{crl} = 1.76$).

The ANCOVA analysis with the S-STEM post-intervention attitudes survey response, with the pre-intervention survey response as the covariate, did not indicate a significant group difference between the treatment (simulation) group and the control (non-simulation) group, $F(1, 80) = 0.37$, $p = 0.54$. The result of the MANCOVA analysis with the S-STEM sub-scales (i.e., STEM attitudes & STEM career interests) was not significant either, $F(2, 79) = 0.31$, $p = 0.73$. The result suggested that there was no significant effect of simulation-based collaborative learning, in comparison with the manual-only condition, in reinforcing students' confidence and efficacy in STEM subjects and their interest in STEM careers.

4.1.1. Qualitative observation: embodied meaning making and joint feedback

Two salient themes emerging from the qualitative data would help to explain the benefit of the flight simulation for the science knowledge development: (a) communication- and action-embodied meaning making, and (b) the joint feedback process. It was found that collective and speeded flight operation, requiring not only a shared understanding but also a collective, speeded enactment of the space flight communication protocols as well as flight-control procedures, have motivated and necessitated conceptual comprehension and procedural knowledge development. Conversations among the flight personnel and mission control facilitated the externalization and constant monitoring of the crew's shared understanding of flight operations and the related science and engineering concepts (e.g., Reaction Control System or RCS, hydraulics). These flight communications comprised advices (e.g., “Mission Control, this is Mission Commander; be advised we are receiving a caution and warning on the APU system.”), announcements (e.g., “Check Hydraulic Pressure – normal is 3000psi” or “Automatic main engines throttle down to 65%”), responses (e.g., “Flash evaporator is operational”), and confirmations (e.g., “FWD RCS He manifold isolation 1/2/3 to open Confirmed”). Frequently, flight crew members were required to not only verbalize but also *embody* science/engineering concepts in a series of shuttle operations, as the following observation notes demonstrated.

> Mission commander reported: “APU/Hydraulics (1/2/3) to Start” while looking for and pressing the corresponding buttons on the control panel.
> Pilot observed the commander's movement attentively, helped to locate the buttons, and checked the positions of the buttons being maneuvered, confirming: “APU/Hydraulics (1/2/3) to Start, confirmed.”

> Mission control advised, “Go for cabin leak check.”
> Mission commander and the pilot both looked at the computer screen attentively and tried to locate the targeted visual display on the screen (i.e., cabin pressure gauge for possible depressurization). The mission specialist who sat behind now stood up a little, extended her body toward the screen before the pilot, and tried to point at a numerical symbol on the pilot's computer screen.
> The pilot then reported, “760.” The facilitator added, “760 torr, which is normal.”
> Mission commander responded to the mission control, “Cabin lead check confirmed, normal.”
> Notably, participants' conceptual verbalization and embodied enactments were augmented by instant system feedback, comprising context-sensitive, multimedia display of the flight system symbols on the computer screen as well as verbal confirmations/responses from their teammates (e.g., “Hydraulics main pump pressure (1/2/3) to Low *Check*!”). All members, required by their team roles and the communication protocol, had to check, read, and interpret task-specific symbols displayed by the computer simulation, as shown below.
> Mission Control reported the flight level, “35000 m, 28000 m …”
> As advised by the mission control (“Check flash evaporator is operational”), the commander checked and reported the (Freon) evaporator from the visual display (showing below 60°).

An interpretation of the above observations is that simulation-based flight communications and collaborative shuttle operations enabled and reinforced a joint, feedback-based learning loop, in which students collaboratively and iteratively monitored each other and interacted with the simulation system to get combined feedback on the application of domain-specific concepts and procedures.

As observed and self-reported during interviewing, simulation participants portrayed emotional engagement with the flight simulation in both immersive contexts. Recurrent utterances from participants (e.g., “oh crap,” “sorry guys, I tried,” “oh, good,” and “nice … easy, easy … slow”) conveyed sense of immersion and varied psychological experiences. Participants also appeared to gain a sense of achievement when they successfully completed a challenging mission; they would cheer and give each other an exuberant high five. Yet such an engaged, affirmative experience of the flight simulation, based on the survey results, did not render additional benefit (in comparison with non-simulation, manual learning) in promoting a positive disposition toward STEM in general.

4.2. Effect of immersive contexts

The ANCOVA test examining the differential effect of the immersive contexts of the simulation environment (exclusive space vs. classroom) on post-intervention science knowledge test performance, with the pretest score acting as the covariate, did not indicate a significant result, $F(1, 17) = 1.21$, $p = 0.29$. The finding failed to provide evidence for the learning effects of varied immersive contexts of the simulation program. It should be noted that the observed power for the analysis was only 0.18, suggesting that a low sample size in each immersive context ($n = 10$) may have reduced the chance of detecting a true group difference. Actually, there is a numerical difference between the two simulation groups favoring classroom simulation ($M_{classroomsim} = 62.36$, $SEM_{classroomsim} = 5.38$) instead of exclusive-space simulation ($M_{exclusivesim} = 53.49$, $SEM_{exclusivesim} = 5.69$).

The ANCOVA analysis with the S-STEM post-intervention attitudes survey response, with the pre-intervention survey response as the covariate, did not indicate a significant group difference across the two contexts of immersion $F(1, 15) = 0.17$, $p = 0.68$. The result of the MANCOVA analysis with the two S-STEM sub-scales (i.e., STEM attitudes & STEM career interests) was not significant either, $F(2, 14) = 0.12$, $p = 0.89$.

4.2.1. *Qualitative observation: competition between sensory immersion and collaborative conceptual processing*

The thematic analysis with participants' participation behaviors indicated that sensory and physical immersion in the exclusive-space simulation fostered the procedural practice of the flight operations, but may have generated distractions from debriefing and impeded meaning-making discussions about each flight operation for deep conceptual understanding. In the exclusive space flight simulation, the background sound effects were loud, making it difficult for the team to engage in verbal debriefing. Even the scaffolding by the facilitator on the visual data display (e.g., the landing system radar) was intermittently overwhelmed by the background sound. The physical set-up of the exclusive-space flight team's seating (check Fig. 1), simulating the real-life shuttle environment, forced individuals to concentrate their visual and psychomotor engagement only on individual computer screens and consoles nearby, rather than their peers. The exclusive-space setting also lacked a shared information presentation object (e.g., a projected, shared screen presentation in the classroom simulation setting). Hence peer mentoring on the flight communication protocol and flight-control procedures could only be conveyed via headset communication. It would be difficult for a teammate (e.g., mission specialist seated on the second row) to direct others' attention to a visual symbol on his/her own computer screen when explaining or questioning on a related flight-operation concept or procedure.

More importantly, by accelerating the sensory stimulation the exclusive-space simulation appeared to generate a stronger degree of time pressure among participants, making them strive to *complete* rather than *comprehend* a procedure. Voluntary occurrences of reflective, ‘intellectual’ moment before or after the trial of a flight operation were sporadic in the exclusive-space simulation setting. Compared with the classroom setting, more participants in the exclusive-space setting failed to describe or explicitly connect their flight-operation actions, communication protocols, and computer-assisted visual outputs using the formal knowledge of the engineering system provided in the student manual. This observation suggested that those participants, in spite of high task engagement, might lack effort in content processing to develop a system understanding of the multi-embodied science knowledge embedded in an exclusive-space simulation.

In comparison, the teams in the classroom simulation were found to be less contested by the sense of emergency and less restricted by the physical setup. Without the mediation of headsets and background sounds, there were obviously more reciprocal interactions among teammates. These interactions include peer inquiry and proactive tutoring on how to express a system concept and syntax in the flight manual, the interpretation of diverse visual symbols in the flight simulation output, and the identification of control/input panel elements related to an operative procedure. In comparison with the exclusive-space simulation, the classroom setting provided more shared physical space (or more freedom for space sharing). It was observed that a teammate would step away from his/her seat and walked toward another's computer station to monitor and assist a control panel operation or the reading of simulation-system signals. In certain cases, the facilitator had to step in to guide crew members to focus on individual responsibility, “Excuse me, Mission Control, you have to focus on this (the computer screen that displays the system status). You don't tell her how to fly!” Actually, the facilitator was found walking around the simulation space and occasionally pinpoint the targeted concepts on the computer screen or in the flight manual for students.

Yet intermittent environmental interruptions, such as broadcasted school announcements and/or routine classroom vacuuming that occurred during the after-school hours, composed an interruption of the simulation flow in the classroom setting. Associated with a reduced level in sensory and physical immersion were more frequent observation of boredom or idle moments (e.g., yawning) and task-irrelevant social chats among crew members. In spite of this, high attentiveness and task engagement were displayed by the participants when they performed a challenging, hand-eye coordination task, such as the landing of the space shuttle that requires a skillful control of the flight gear and a fluent reading/monitoring of the system output on the computer screen.

5. Discussion

The study found that immersive-simulation-based collaborative learning promotes students' learning about the dynamics of the space flight system. Both simulation interventions, in comparison with the no-simulation control condition, better promoted students' knowledge test performance. Yet the study did not find evidence supporting the benefit of the simulation interventions (versus Astronaut Challenge manual learning) in promoting students’ general confidence and efficacy in STEM subjects and their interest in STEM careers. The knowledge test and attitudes survey results did not indicate a significant differential effect of the two immersive contexts of the simulation on the learning outcomes. The finding is generally in agreement with the conclusion of Norman et al. (2012) on the equivalent learning effectiveness of high and low-fidelity simulations. On the other hand, qualitative findings suggested that the higher level of sensory immersion may have fostered task engagement and procedural practice while impeding collaborative debriefing and conceptual comprehension during simulation-based learning.

5.1. Simulation-based content encoding and joint problem space

The study found the advantage of simulation, in comparison with no-simulation manual learning, better promotes science knowledge development. This finding supports the previous studies reporting the effectiveness of computer, three-dimensional simulations in enhancing science learning (Koh et al., 2010; Rutten, van Joolingen, & van der Veen, 2012; Urhahne, Nick, & Schanze, 2009). A potential explanation is that the simulation-based representation of the science (space-flight) system enables students to develop appropriate mental representations (e.g., conjectures and understanding) that correspond coherently to the external, conventionally established (formal) system of science (Goldin, 1998; Kosslyn, 1980; Mercier & Higgins, 2014). Qualitative data suggested that the interactive flight simulation facilitates the development of multiple systems of cognitive representation via multi-embodiment. Specifically, the multi-embodied content encoding of the simulation participants includes verbal/syntactic expression (scientific vocabulary and syntax conveyed by student manuals and oral flight communications), imagistic configuration (computer visuals and simulation-based, spatial cognitive configurations of the engineering system of a space flight), and kinesthetic encoding (i.e., body movements and interactions with shuttle switch control panels) that captures the ‘feel’ of the science while solving flight operational and emergency problems. This observation is in agreement with prior research on the educational value of multiple representations in the learning of complex scientific concepts (Ainsworth, 2006). It also supports the claim of Dede, Salzman, Loftin, and Sprague (1999) that multisensory immersive simulation can create “real-life referents” for complex scientific concepts or phenomena, and hence help students to “perceptualize” abstractions in science (p. 282).

In this study, students work as a collaborative group that shares and works on joint problems (e.g., a series of space flight missions or tasks). During the collaborative problem solving process, their psychomotor interactions with the flight simulation as well as structured, protocol-oriented verbal interactions with groupmates have contributed to joint, feedback-based meaning making (e.g., a shared understanding of related concepts and procedures). Such an observation supports the claims of prior research that it is important to create a joint problem space in computer-supported collaborative learning, in which group members will converge on a shared meaning of the problem and the solution processes to make sense of scientific phenomena (Mercier & Higgins, 2014; Roschelle, 1992). The finding on the salient role of joint feedback in the simulation-based, collaborative learning process also supports the theoretical perspective of inquiry that describes learning as an explicit feedback loop — an iterative cycle of practice, observation, reflection, and action (Dewey, 2013; Schön, 1992; Sterman, 1994).

Fig. 1. Exclusive space versus classroom simulation.

5.2. Immersion design and simulation-based collaborative learning

Part of the study findings is in agreement with the literature that suggested the more surrounding the physical dimension of the simulation technology is, the more immersive it will be (McMahan, 2003). Yet the study also indicated that simulation-based learning is not dependent on the physical or sensory immersion of the simulated space. Across the two levels of immersion in this study, there was no significant difference in students' knowledge test performance. This finding supports the report of a previous study on virtual reality environments by Moreno and Mayer (2004) that even though students reported higher levels of physical presence with high (via head-mounted display) rather than low immersion (via desktop computer), higher immersion did not lead to better performance on tests of retention or transfer. The finding is also consistent with the report of Mania and Chalmers (2004) that the level of reported immersion was not positively associated with accurate memory recall in the immersive simulation, and the conclusion of De Giovanni et al (2009) that higher level of fidelity did not better promote skills transfer. But it disagrees with the discovery of Brydges et al. (2010) on the advantage of higher fidelity of the medical simulation in promoting clinical performance and technical skills transfer, or the report of Ragan et al. (2010) that higher levels of immersion can improve performance in procedure memorization tasks. It should be noted that the knowledge test in this current study focuses on the retention and conceptual understanding of the target science and engineering knowledge, more than procedural skills of space flight operation. An interpretation of a non-significant difference in the knowledge test result, according to prior research of immersive simulations (Sowndararajan, Wang, & Bowman, 2008) and fidelity (Hays & Singer, 2012), is that the higher level of sensory immersion or physical fidelity mainly contributes to faster procedural task performance and reduced error in motor or spatial activities, rather than enhanced conceptual understanding.

Specifically, this study found that sensory immersion failed to reinforce debriefing and joint feedback processes to promote learning, while the high fidelity simulation literature has identified feedback and debriefing as the most important features of simulation-based learning (Fanning & Gaba, 2007). Based on the qualitative findings, the enhanced level of sensory and physical immersion (e.g., surrounding sound and physical set-up) has appeared to reduce students' motivation to process and comprehend knowledge embedded in interactions and actions, and restricted their capability to collaboratively explore, monitor, and provide reciprocal feedback to each other during task performance. In other terms, the level of physical fidelity or sensory immersion has failed to reinforce communicative and collaborative learning processes. This finding suggests that using immersive representations to mediate interactions among learners for the inquiry learning of science phenomena, though claimed as a promising direction for technology enhanced constructivist learning (Dede et al., 1999), needs to be further examined and carefully designed. Drawing on prior research (Ackermann, 1996; Colella, 2000; Sterman, 1994), a speculation is that the immersive component per se does not guarantee the enhancement of educational benefit of a simulation activity; rather, designing immersion in a simulation to reinforce not only engagement *in* a problem but also thinking *about* a problem (or the simulated system) is critical for learning.

5.3. Implications and future research

Immersive simulation, as the study findings suggested, helps to create a joint problem space and plunge learners in active interpersonal and simulation-learner interactions for experiential learning. Learning artifacts in an immersive simulation, including the simulation system input and output as well as peer interaction/feedback, have presented a multi-embodiment and a shared representation of the targeted concepts and science system for collaborative learners. On the other hand, immersing learners in a system may fails to provide an exocentric perspective for learners to perform purposeful reflective thinking about the interactions with and dynamics of the simulation system. A corresponding design proposition is to create a simulation-based learning space that will award and scaffold learners to co-explore the system and content via not only first-person role-play experiences, but also observatory or reflective evaluations (e.g., peer- and self-critiques).

The study found that a regular classroom set-up can work as an equally effective and cost-efficient alternative to a surrounding, exclusive-space set-up for 3D science simulations. A design inference, based on the study findings, is that the learning effectiveness of an immersive simulation (especially in the context of conceptual understanding) relies on the functional fidelity more than sensory and psychological ones. In this study, both contexts of the 3D simulations generate similar learning interactions and actions – the way that learners interact with their peers and the simulation environment is generally the same). Hence the level of the functional similarity between the simulated task and the real-world operation in both simulation settings remains similar, which explains the equality of learning effectiveness of the two simulation settings.

Still, much work remains to be done to determine the best ways to use immersive simulations in collaborative learning settings, and to examine the design of physical, functional, and psychological facets of the simulation fidelity to build learning-constructive immersion. Future research should further investigate the aforementioned research issues by involving a larger study sample, and focusing on evaluating procedural and ill-structured problem solving in addition to conceptual understanding as the learning outcomes.

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