Augmented Reality Improved Learning of Lower-level Students by Empowering their Participation in Collaborative Activities

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Abstract: Many studies have shown that augmented reality (AR) can improve learning, but little is known about the mechanisms. To investigate this inquiry, we employed a mixed analysis method to approach the data coming from an experimental study. The quantitative findings showed that lower-level students performed better in the post-assessments for AR groups than for control groups. Qualitative analyses were conducted to explore how AR facilitated the lower-level students' learning. The current findings suggested that: the AR's feature of distributed labor, openness, real-time feedback, and operational symbolic items sustained the lower-level students to engage with higher-level students in problem-solving activity inclusively, jointly, and authentically.

Introduction

Augmented Reality (AR) is a technology connecting virtual objects to the real world (Akçayır & Akçayır, 2017). As AR allows students to learn abstract concepts in a concrete and visualized way, its application in educational settings has demonstrated accelerated growth in recent years.

The positive impact of AR on learning has been demonstrated by many experimental studies (for comprehensive reviews, see Akçayır & Akçayır, 2017; Garzon & Acevedo,2019). Moreover, three studies showed that lower-level students benefited most in learning activities supported by the AR tool (Cai, Wang, & Chiang, 2014; Lu & Liu, 2015; Salmi, Thuneberg, & Vainikainen, 2017).

These findings beg the question, how do AR technologies afford learning? Most researchers explored this question by soliciting students' perspectives. First, AR enabled students to see details better, making scientific ideas more comprehensible and more transparent (Bursali & Yilmaz, 2019; Yoon, Anderson, Lin, & Elinich, 2017). Second, AR supported the learning of content by enabling the memorization of facts and concepts (Cai, Wang, & Chiang, 2014). Third, AR encouraged students to conduct experiments of their hypotheses, allowing them to engage in more reasoning activities (Enyedy, Danish, & DeLiema, 2015). Lastly, AR improved affective aspects of learning, such as interests, satisfaction, and enjoyment (Ibáñez, Di Serio, Villarán, & Kloos, 2014; Lai, Chen, & Lee, 2019).

However, little research explored the affordances of AR by focusing on analyses of the learning process. In effect, the questions of- which features of AR facilitate learning? In what ways? – requires a careful examination of the student-AR interaction in the situation where learning occurs. The insights gained promise to be valuable for informing the design of productive learning environments supported by AR system. Thus, this analysis intends to address a gap in current understandings of AR in learning by addressing the following two questions:

RQ1: Did lower-level students show improvements in AR-supported learning environment?

RQ2: If so, how did AR afford the learning of lower-level students?

Methodology

The methodology is described in following three sections. First, the study design is described in detail regarding the context of data collection and participants. Second, the statistical method for answering the RQ1 is introduced along with the rationale and hypotheses. Third, the analytic framework used as a lens to understand the role AR played in students' engagement with each other, and the content used in order to address RQ2 is described.

Data

The data analyzed in this paper comes from an experimental study conducted in April 2019, seeking to explore students' collaborative learning experiences with the use of AR technology (experimental group) as compared to a computer method (control group). This AR system was designed by faculty and doctoral students in chemical engineering department for the facilitation of students' learning in a chemical reactor design course. Its shape is a table with a big glass screen on the top. When putting physical totems on the table that represent small reactors, the table simulates the reaction by displaying a supplemental data reaction process in real-time. These data represent the chemical specimens present in each reactor as well as the output of the complete reaction, shown in the form of pie-graphs. The data are computed based on the types of reactors (including batch, CSTR, and PFR) used, their volumes, configurations, and temperatures. By interacting with AR, students are expected to develop an intuitive understanding of the rate law, the role of temperature, and the effects of reactors as they interact in systems. In contrast, the computer method (experimental control in our study), which is based on Python software, is a traditional way to simulate the chemical reaction process representing inputs and outputs in the form of equations and numbers.

Forty-seven students in the course of chemical reactor design participated in the study. They were allowed to form groups of three or four students voluntarily and then were randomly assigned to AR (N=24) and control (computer trials) conditions (N=23). The study design included two parts: First, students were given 20 minutes to collaboratively solve a series of problems authored by the course instructor using AR (experimental) or computer (control) technology (problems were the same for both conditions). Students in the control groups did not need to write the coding on their own, as an exemplar was provided. Next, all student groups engaged in researcher-facilitated focus groups to reflect and report on their learning experiences. The focus groups lasted about fifteen minutes. Both task activities and focus groups were video-recorded.

Pre- and post-assessment were intended to evaluate students' understandings of the impact of temperature on the conversion rate in a given reaction. This assessment was a modeling task in which students graphed and authored narratives about their understandings of the system. Students completed the assessment sheet individually one day before the experiment. Then, they got their sheets back after the experiment and had a chance to modify their pre-answers. Two doctoral chemical engineering students evaluated all assessments on a 0-10 scale for both graphical and narrative responses.

Analytic approach for RQ1

Participants were classified by their pre-assessment performance levels as below average (0~4), around average (5~6) and, above average (7~10). The mean differences between different levels in pre-assessments and post-assessmentss were tested for both AR and control groups. There were two hypotheses: First, the mean differences between different levels of students in pre-test were statistically important for both AR and control groups; second, the mean differences between different levels of students in post-test were statistically significant for only control groups, not for AR groups. A non-parametric method, Kruskal-Wallis H test, was applied because the data violated the assumption of normal distribution.

Analytic approach for RQ2

The second part of the analyses attended to the experiences of individual students in task activities. A qualitative approach was employed as it allowed factors that contributed to learning to emerge from analyses of the learning process and interactions.

To reveal how AR tool facilitated learning of lower-level students, two criteria were applied to select the cases. First, students were identified as performing below average in pre-assessments; second, these students showed significant improvements in the post-assessments. Thus, a total of 6 participants were selected, and their pre- and post-scores were shown as below (See Table 1).

Table 1. Cases for qualitative analysis

Names	Pre-scores	Post-scores	Improvements
Alice	4	8	4
Matt	3	9	6
Leo	4	9	5
Robert	2	10	8
Yvonne	4	9	5
Asher	3	9	6

Two theoretical lenses were employed to approach the second question. One is the role and impact of *mediating artefacts* on learning, a concept has been illustrated and developed by researchers, including Vygotsky (1978) and the activity theorists (Cole & Engeström, 1993). The basic premise is that the artefacts involved in a learning situation impact the way that people perceive, talk about, and make sense of the phenomena. This analysis used mediating artefacts as an analytic lens to understand how AR afforded learning in the group problem-solving activities.

The other theoretical concept was *legitimate peripheral participation* (LPP) (Lave & Wenger, 1991). From this perspective, learning is situated in social contexts and interactions, and it is achieved through an increase in participation of authentic practices of a community. Moreover, it suggests that newcomers become acquainted with a community of practices (CoP) through participation in peripheral yet legitimate practices, and through interaction with experts (Wenger, 1998). Our analyses applied this theory to address the learning experiences of lower-level students as they share several characteristics with newcomers, such as lower knowledge level and self-confidence. In this sense, the community of practices is conceptualized as the knowledge and skills required to carry out group activities; and the experts refer to the high-level students within the chemical engineering discourse. One thing should be noted, as the task time for each group only lasted 20 minutes, the long-term transition- from LPP to full participation-was not of concern in this analysis. Rather, it focused on what peripheral practices were available to support the learning of the lower-level students in AR- supported environment.

Additionally, the literature of collaborative learning suggests that the interaction between lower-level students and higher-level students might be detrimental to the former's learning in three situations. Specifically, the higher-level students can dominate group discussion, excluding the lower-level students in problem-solving process (Bishop 2012; Esmonde, 2006). Second, the lower-level students might not keep up with higher-level students, thus left behind (Dookie, 2015). Third, the higher-level students have been shown to ask lower-level students to work on basic procedures (e.g. calculation), missing opportunities to engage in meaningful practices (e.g. reasoning) (Dejarnette & Gonzalez, 2015; Wood, 2013). These, in effect, respectively the concerns center on issues of inclusiveness, inconsistency between individual and collective, and authenticity in collaborative learning settings. Thus, this analysis was particularly interested in how the AR technology helped the lower-level students to engage with higher-level students in problem-solving activities *inclusively*, *jointly*, and *authentically*.

Finally, both the verbal and non-verbal data were carefully examined. We were interested in including the non-verbal elements in analyses for three reasons: First, students tend to use physical acts to facilitate their expressions of conceptual ideas (Reynolds & Reeve, 2002). Second, gestures such as tapping and eye gaze can show the foci to which students pay attention (Barron, 2003). Thirdly, students' bodily orientations in group tasks help to reveal individual's positioning emerged in group dynamics (Dookie, 2015).

Results

Quantitative findings

The Kruskal-Wallis Test showed that: in computer groups, both students' pre-assessment scores (H=19.23, p <.001) and post-assessment scores (H=7.77, p=0.02) were significantly different for different levels of students; however, for AR groups, only students' pre-assessments scores were significantly different for different levels of students (H=18.99, p < .001); while students' post-assessment scores were not significantly different for different level of students (H=3.63, p=0.16). This suggested, after students interacting with technological tools, the academic achievement gap still held for computer groups, not for AR groups. Below is a figure comparing students' mean improvements according to their pre-levels between computer and AR groups.

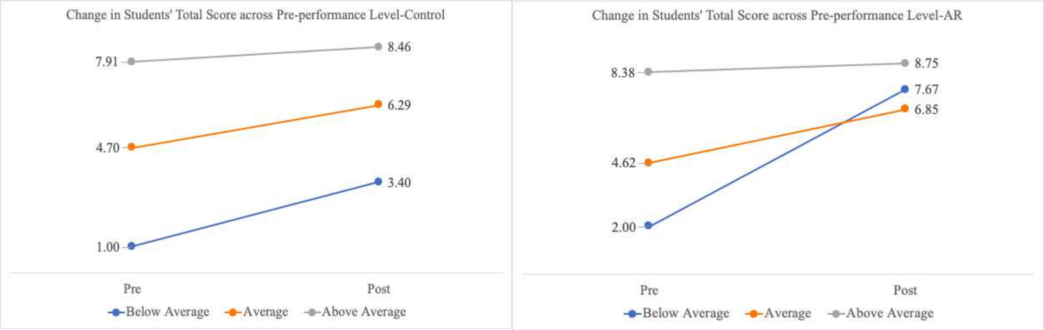

Figure 1. Changes in the mean of students' total scores across pre-performance level- Control v.s. AR.

A pairwise comparison was performed to explore which groups (pre-performance levels) were different to which other groups. The findings showed that, before the study, there were statistically significant median differences between the below average (1) and above average (7) (p < .001), and between the around average (5) and above-average students (p = .016) in computer groups. Similarly, in AR groups, there were statistically significant median differences between below average (2.5) and above average (8.5) (p < .001), and between around average (4) and above-average students (p = .005).

However, after the study, the significant median differences between the below average (1) and above-average students (9) still existed for computer groups (p = .024), but not for AR groups - below average (9) and above average (9). This result indicated that the below-average students obtained higher gains for AR groups but not for computer groups.

Qualitative findings of AR affordances

AR helped lower-level students be included in group work

AR afforded the inclusiveness of collaborative activity in two ways. First, its feature of *distributed labor* assigned certain roles to each individual involved in the learning space, and no one's role could be replaced. Specifically, to initiate an activity, a group of students set up three things ready according to conditions in the problem: volume, temperature, and the (configuration of) reactors. Of the AR table, a volume and a temperature knobs were on the left and right side respectively, and in the middle was a large screen where students set up reactors. Because of this physical layout, participants usually took up a role based on their physical proximity. For example, students who stood near the left/right of the table were responsible for adjusting volumes/temperatures; and students who stood in the middle tend to manage the configurations of reactors. Typically, participants coordinated the group task by playing their unique roles and they rarely took up the roles of others. The following excerpt showed how the role of volume adjuster emerged.

Table 2. Matt's role of volume adjuster

Participants	Verbal	Non-verbal
Matt	Wait! This is also not at 60 liters	Pointing to the volume number displayed on the screen
Nash	Oh, it is not?	Looking at the volume number
Louis	Oh year, it is not. Can you change that?	Looking at the volume number and then looking at Matt
Matt		Spinning the volume knob

A basic knowledge for operating the AR table is that the volume and temperature need to be set before putting the reactors on the screen in order to link the specifications to the particular reactor. If users didn't follow that order, the AR would yield wrong results, leading to wrong concepts of how volume/temperature affects the conversion rate. However, in the above excerpt, participants forgot this rule at the beginning. It was Matt who stood near the volume knob who identified it. Before he spoke up, he double-checked the volume size by shifting his head between the screen and the problem sheet. Then, his peers noticed and asked him to change that. This showed that, Matt's physical proximity to the volume knob not only invited him to play a volume-relevant role, but also made other students in this group acknowledge his role. The following conversations in Matt's group demonstrated that his role was stable during the group task: if one wanted to change the volume, he would ask for Matt to do it. Thus, because of the distributed labor assigned by the AR, the participation and the engagement of lower-level students in group activities are included and valued.

The second feature of the AR that afforded inclusive participation in collaboration is *openness*. Openness, in this context, especially meant that all information and all functions displayed on AR table were accessible for all participants. As in some situations, the coordination between two students was more frequent, leaving the third person out. However, the third person still can enter into the content space of the other two and follow the progress in this AR-supported learning environment (see Figure 2).

Figure 2. Leo (left) observed the peer's practices and the associated results.

Although Leo's peers stood close to each other to work on the AR screen, the temperatures they tried and the associated conversion rates were still visible for Leo because each piece of information provided by AR was open to all. Evidenced by Dookie (2015)'s study, the lower-level students had few opportunities to learn when being physically blocked out of the learning content and resources by higher-level students. This analysis, however, demonstrated the negative effects of physical block in group learning could be eliminated in a larger AR-supported learning space.

AR enabled lower-level students to keep pace with group progress

Two phenomena were observed that related to how AR balanced the inconsistent speed of problem-solving between lower-level students and higher-level students. One was associated with students' roles. For example, in Matt's group, every time when the other two completed a question and prepared to start a new one, they would ask for Matt to change the volume. However, if, at that moment, Matt still thought about the previous question, he would say "hold on" and would not change the volume until he figured it out.

In another situation, the AR's feature of *real-time feedback* would enable the lower-level students to re-engage with the task after independent thought was evident. For example, there were several moments when Leo did not articulate his understanding (see figure 3). He stood far away from the table, thinking independently, while his peers still did trials on the AR screen. However, his independent thinking did not last for long. Every time when the new real-time feedback generated by the AR tool, Leo would go back to the table and watch the result. Thus, even though Leo spent time dealing with his own thoughts, the real-time feedback displayed on the screen drew his attention back, ensuring that he did not miss the group progress and the newly generated learning contents.

Figure 3. Leo was thinking independently (left) and re-engaged with the group progress (right).

AR scaffolded lower-level students to engage in conceptual talk

Two features of the AR were found to facilitate students' participation in conceptual talk. One was the *operational symbolic items* within the AR system, including the volume, the temperature, the different types of reactors, and so on. Each of them was represented by concrete objects in the AR-supported learning space but were scientific concepts in nature belonging to the discourse community of chemical engineering. Thus, as students manipulated and reasoned with the concrete objects, they were also working with the conceptual meanings embodied in the objects.

Table 3. Leo made sense of the Levenspiel plot

Participants	Verbal	Non-verbal
Leo	I guess….	Looking at the problem sheet and thinking about something
Tom	This is visualizing like a PFR thing that where they add the CSTR one after another	Gesturing a plot
Joe	The Levenspiel plot	
Tom	Yeah, the Levenspiel plot	
Leo	Oh, that's beautiful	
Leo		Thinking around 5 seconds
Leo	So PFR is just under the curve, right?	Gesturing the plot
Tom	Yeah, PFR is under the curve, and CSTR is like that	Gesturing the plot
Leo	So we can use the PFR, because we don't have all CSTRs	Pointing to the PFR on the AR table

In this conversation, Leo and his peers discussed the ways to solve the following question- "Without actually placing them, how can you model 10 6L CSTR in series?" Since there were only 3 CSTRs on the AR table, Leo, in the beginning, did not understand the point of this question. Later, reminded by his higher-level peers, Leo recalled that the conversion rate of a lot of CSTRs was approximate to that of PFR according to the Levenspiel plot. Then, Leo saw there were several PFRs on the AR table, so he suggested to use PFR instead to solve this question.

In effect, the key to solve this question was an understanding of the Levenspiel plot. Tom raised this idea after he saw a PFR on the AR table. However, Leo completed forgot this concept and spent some time thinking about what it was. Without Tom, Leo might not solve this question on his own. Thus, Leo's learning was helped by his higher-level peers, who were able to connect the symbolic items at hand with the concepts and ideas acquired in previous academic experiences.

Second, AR triggered conceptual thinking through its feature of *real-time feedback*. Most of the questions in the problem sheet were finding out the temperature that gave a maximum conversion rate at a given volume/type of reactors/configuration of reactors. Thus, the real-time feedback feature of AR allowed students to quickly initiate different trials, in which they articulated their reasoning and developed an understanding of the effects of temperature on the conversion rate based on multiple results.

Table 4. Leo's reasoning of the effects of temperature on the conversion rate

Participants	Verbal	Non-verbal
Joe	What do we start?	Preparing to adjust the temperature knob
Leo	350	
Tom	Yeah, 350	
Joe		Adjusting the temperature
Tom	It's 63%	Reporting the conversion rate displayed on the screen
Leo	I guess, we just take it off and change the temperature	Laughing
Tom	Do you wanna try 375 or something?	Taking up the reactor
Leo	Yeah	Looking at the temperature number
Joe		Adjusting the temperature
Leo	That is decreased.	Looking at the conversion rate
Leo	So we try 315 now	Looking at the temperature number
Joe		Adjusting the temperature
Tom	Oh, 315 we got 71%	Looking at the conversion rate
Leo	So we decrease the temperature a little bit	Looking at the temperature number

In this conversation, Leo and his peers were searching for the temperature that yielded the maximum product in a batch reactor. They quickly developed the strategy of trial and error to find out the temperature. When Leo said "so we try 315 now" he had got an idea that the temperature and the conversion rate were negatively correlated. Because when temperature shifted from 350 to 375, the conversion rate was decreased from 63 percent. Because of that, he suggested a lower temperature "315" to confirm his theory. Then, at this temperature, the conversion increased to 71%. Thus, he continued to propose a lower temperature to try. During this process, Leo made suggestions based on the relationship he perceived between throughput and temperature. That said, he did not make his reasoning explicit. Instead, his reasoning process and recommendations were mutually fed into each other and developed as the experiments progressed.

Discussions

The results of this study showed that our AR system supported lower-level students in participating in several processes and activities related to solving chemical engineering problems. One practice that was significant for lower-level students' learning was an engagement of conceptual talk, through which they gained chances of shifting their thinking. The mechanisms of how AR made conceptual ideas accessible for lower-levels students will be discussed in contrast with that of the control groups.

The AR technology structured this sense-making activity to be friendly to lower-level students from two aspects. First, AR groups expressed their ideas using everyday language while talk in control groups often involved abstract terms. For example, when reporting a conversion rate, the former would say "that is 0.55" whereas the latter said, "X equals 0.55". The expression style of control groups might result from their interactions with Python coding, which displayed such information as equations, formulas, and denotations of concepts. They even talked about concepts that were not clearly referenced in the immediate situation, such as Fa (flow rate) and τ (residence time), preventing the lower-level students from engaging in group discussion. In comparison, most of the talk of AR groups used everyday language and associated references with certain physical objects involved in the AR system. Thus, lower-level students in AR groups had an easier time making sense of what other group members talked about. The mediating effects of artefacts on language have been identified and described by many studies. For example, Sfard (2008) observed that the symbolic items, such as algebraic expression shaped a *technical conversation*, while the concrete objects and images facilitated a *colloquial conversation*. Our findings further suggested that the latter was more conducive than the former for the learning of lower-level students in collaborative activities. However, how the communicative language was mediated by technology and how it supported/inhibited the participation of lower-level students require further investigations by comparing AR and control groups.

Second, the sequence of doing trials and reasoning matters. For example, to find out a temperature that maximized the conversion rate of a given reaction, control groups began by talking about possible relevant equations, based on which they guessed the range of temperatures; then, they tested their ideas using Python coding. In contrast, the real-time feedback feature of AR allowed for low-risk trials and data collection; thus, students preferred starting with doing experiments first and then reasoned their practices in light of findings (as shown in Table 4). In this way, the reasoning process was embedded in concrete data, and the conceptual ideas were naturally emerging as the experiments progressed. Therefore, the lower-level students in AR learning space were able to engage in the reasoning talk due to the reduced levels of abstraction in the sense-making activities. Based on such data, we considered that the computer tool sustained the traditional way of carrying out mathematical-related activities, such as writing down the equations and doing calculations, which maintained the original structure of students' performances in class. Rather, our AR system privileged the practices of "learning-for-now" over the "reviewing-the-past", thus avoiding unbalanced participation structured by students' pre-achievement levels.

In addition to conceptual participation, our AR system engaged lower-level students in technological-manipulating practices (adjusting volumes/temperatures and setting up the configurations of reactors), which were simple but meaningful for their engagement. Similar to newcomers in a CoP, the only way for lower-level students to access community activities is through legitimate peripheral participation (Lave & Wenger, 1991). The distributed labor demanded by AR provided such opportunities. On the one hand, operating this technology was low-risk and did not require much knowledge of the CoP (*peripheral*); on the other hand, this work was necessary and valued to fulfill the community goals (*legitimated*). In effect, the theory of CoP implies the power that experts have upon newcomers as they can determine whether "to confer legitimacy on the newcomers" (Floding & Swier. 2012, p.199). However, the AR technology in this study balanced the power between higher-level students and lower-level students by directly assigning them legitimate roles. Also, as shown in the results, the irreplaceable role of lower-level students in group work further supported their authority in more central practices by allowing for independent pacing in collective sense-making activities. Thus, taking up the distributed labor roles gave permissions to lower-level students to access the group discourse, to observe and learn from higher-level students, and to make sense of the community knowledge.

Implications

One implication of this study centers on learner-centered design. Integrating technologies, whatever AR or other tools, into the classroom is a central topic in both research and practice. For educators who are committed to ensuring equitable participation in collaborative learning, this study suggests a possible way based on the unique benefits of our AR system: the incorporation of technological tools which assign irreplaceable but manageable roles to each individual (*distributed labor*), allow displays to be accessible to all students (*openness*), and afford the reduction of levels of abstractions in group communication (*real-time feedback* and *operational symbolic items*).

Another implication from this study can be drawn regarding research methodology, specifically concerning the data analysis of non-verbal acts. This analysis replicated previous findings in that non-verbal acts served to shape participants' joint attention (by pointing to certain content) as well as assisted the expression of unfamiliar concepts (as shown in Table 3). Moreover, it suggested one additional function, which is the physical engagement of technology can be a productive form of engagement for cognitive participation in authentic activities. This point has been discussed in detail in previous sections. Since the learning environment, supported by technologies, welcomed embodied involvement, participants' non-verbal acts undoubtedly contributed to their learnings. The functions of non-verbal acts in both individual and collective meaning-making in the learning context of technology are worth investigating in future studies.

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