The effects of learning analytics hint system in supporting students problem-solving

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ABSTRACT

This mixed-method study examined the impacts of a learning-analytics (LA) hints system on middle school students' problem-solving performance and self-efficacy (SE). Students in condition A received the LA hint system, students in condition B received a static hint system that contains the same set of hints but without the LA mechanism, condition C was a control group that no hints were provided. The statistical results showed that the problem-solving SE for students who engaged with the LA hint system improved significantly. Student interviews revealed that real-time supports and in-time positive feedback played key roles in supporting their SE growth. Moreover, student-generated quantitative and qualitative log data were collected for interpreting the research outcomes. The quantitative logs provided an in-depth examination of problem-solving strategies across the conditions while the qualitative logs provided another perspective to understand students' problem-solving status. Implications for future implementation of LA-hint system in virtual PBL environments were provided.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in interaction design**.

KEYWORDS

datasets, neural networks, gaze detection, text tagging

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1 BACKGROUND & INTRODUCTION

Problem-based learning (PBL) is an instructional approach in which students learn through facilitated problem-solving that centers on a content-related complex problem [11]. It has been applied in various educational levels across diverse disciplines since it was introduced from the medical education field [1]. Empirical studies showed that PBL improved students' content knowledge learning, problem-solving skill, self-efficacy, and learning motivation [22, 27, 36]. Researchers and educators have taken the initiative to adapt PBL scenarios to virtual platforms along with the advancement of virtual learning environments. The virtual PBL environments enabled educators to create more authentic and immersive learning experiences to facilitate students' knowledge and skill acquisition [33].

Although PBL has proved to be a promising approach to facilitate knowledge and skill gaining, previous studies have revealed that there are two main challenges that learners, especially at K-12 level, might encounter [23, 30]. Firstly, the problem itself is ill-structured that does not have a single correct answer [11], students have to conduct a series of tasks such as gather useful information or generate hypotheses to develop feasible solutions [16]. Secondly, PBL is a student-centered instructional approach [4]. Instructors mainly play the role of facilitators and are not supposed to provide direct answers to students. Instead, they can only offering indirect instructions like hints or question prompts to support students problem-solving [9]. Students should rely on their own to achieve the solutions, which is even more challenging for those who are new to PBL.

To better facilitate students especially for those who are new to solving an ill-structured problem in a student-center learning environment, researchers have started to adapt the virtual PBL environments by allowing the environment to deliver students with some aids. For example, previous research tried to embed supportive systems such as hints [2], question prompts [24], or widgets [31] to assists students. The outcomes from these studies showed that students were better supported and their problem-solving and learning performance were improved too. However, many of these systems lack individualized design. For example, the hints sent to students were differentiated by individuals nor aligned to their pace, sometimes a hint student received at a certain time-point often did not match the tasks students had at the moment. The lack of individualization limits the system's potentials in alleviating students' challenges in PBL, and might ultimately compromise the expected learning outcomes system [13]. Thus, it is meaningful to design better supporting systems in virtual PBL environments that could meet students' needs on a more individualized level [8].

2 PURPOSE OF STUDY

The recent emerging of the learning analytics (LA) field offered an opportunity for educators to provide students with individualized supports. When students are engaging with the virtual PBL environments, large amounts of log data will be generated [17]. The log data can capture a thorough trajectory of each student's unique

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problem-solving patterns. Plus, the logs were collected in a real-time manner [35], which means researchers and educators could take advantage of the logs to understand students' real-time status and thus, provide in-time intervenes. However, there is a lack of empirical studies that either designed or applied LA-incorporated supportive systems in virtual PBL environments to assist students, even less provided both quantitative and qualitative outcomes to evaluate the effects and user feedback.

Therefore, in responding to the need for more individualized supports in virtual PBL activities and to address the research gap. Researchers developed an LA-incorporated hint system that delivers individualized hints to students in a virtual PBL environment. The goal of this study is to evaluate the effects of the LA hint system and examine its impacts on students' problem-solving behaviors.

More specifically, the researchers are interested in whether the system could help students in solving the problem and how exactly it would impact students' problems-solving strategies or behaviors:

RQ1. What is the effect of the learning analytics hint system on students' problem-solving performance? How does the system affect their problem-solving performance?

Moreover, the ill-structured nature of the problem and the student-center learning environment is always challenging to learners especially for those who are new to PBL. If the system does help students tackle the challenges and improve their problem-solving performance, it is meaningful to know whether students would feel more confident about their ability in dealing with PBL activities after the intervention. In other words, the researchers are also interested in exploring if the system would impact students' self-efficacy on problem-solving in virtual PBL environments:

RQ2. What is the effect of the learning analytics hint system on students' self-efficacy in PBL activities? How does the system affect their self-efficacy in problem-solving activity?

In addition, it is valuable to explore students' behavioral log data to examine whether and how will hint systems impact students' problem-solving patterns. Thus, the last research question focus on applying learning analytic techniques to analyze students' problem-solving behaviors when they are engaging with the LA hints system:

RQ3. What problem-solving behaviors are revealed by learner behavioral log data across three conditions?

3 METHODS

3.1 Virtual PBL Environment & Participants

The virtual PBL environment in this study is called Alien Rescue (AR), it is aligned with national science standards to teach the space unit in 6th-grade science classes. In this environment, students play the role of young scientists to relocate six displaced alien species to habitable planets in our solar system. These 6th graders were tasked to acquire and practice their problem-solving skills as they explore, hypothesize, and generate their solutions in a self-directed manner. Figure 1 presents the screenshots of the AR environment.

A total of 285 6th grade students from 17 classes in a middle school locates in the southwest of the United States participated in this study, they engaged with AR in a total of 10 class sessions. According to their science teachers, this group of students was new to virtual PBL activities, and they had similar backgrounds in interacting with virtual learning platforms.

Figure 1: AR Environment

3.2 The Learning Analytics (LA) Hint system

The LA hint system is developed by the researchers and then embedded in the AR environment for this study. Rather than delivering static and fixed hints, the system presents students with real-time hints to assist their problem-solving progress. The hints delivered to students were presented on a pop-up window at different times tailored to their own pace, the hints delivered also differs upon students' problem-solving actions. Some hints would be presented multiple times based on students' progress too. In this case, students with different problem-solving patterns would receive individualized supports that tailored to their real-time needs. The design of each hint message is informed by the Adaptive Character of Thought-Rational learning theory (ACT-R) [3], the theory proposes that learners should be treated as rational agents who are actively obtaining the information instead of passively receiving it. For example, all hint messages were written in an encouraging and suggestive tone (see Appendix), and no declarative language was used since the goal of the hints is to facilitate rather than give direct instruction. Plus, ACT-R also indicates that knowledge could be divided into smaller pieces when delivered to learners. Along this line, a key strategy performed by the hint system is that it provides students with a series of sub-tasks, which guides students progressively to generate their solution plans. Besides, to ensure the design and the language of the hint message are accessible to middle school students, all hint messages were examined by middle school science teachers for refining and improvement.

Moreover, the design for some of the hints, such as the timing for a certain hint to pop up, is aligned with the idea of viewing LA as bootstrapping process proposed by Winne [34]. For instance, once a student accessed the *Alien Information Center* the first time in the environment, the students who stayed longer than 17 seconds would receive a different hint message compared to those who stayed shorter than 17s. The length – 17s is determined by the outcome of processed log data from 6th graders who used the same virtual PBL environment in the same school from the previous year, which is the median of the all lengths performed by students. The *Alien Information Center* contains crucial information for students to generate final solutions, students who stayed less than 17s are expected to stay longer to gather more information. Thus, the hint sent to these students contains information that encourages them to stay longer and explore more. While the hint sent to those who stayed longer than 17s then contains other information that guides them for further tasks. This is an example of how LA hint system provides individualized hints based on students' progress and actions, a section of the hint system with details can be found at Appendix.

Figure 2 presents a screenshot of a hint that popped up to students. The whole hint box would pop up accordingly as students progressing through the activity. After viewing the hints, students can close the hint box by clicking the *Mail* icon at the bottom. If needed, they can also revisit the previously popped hints by clicking the *Mail* icon again.

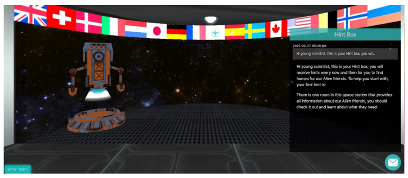

Figure 2: LA Hint System for Condition A

3.3 Research Setting

The participating classes were randomly assigned into three conditions. Participants in condition A (n = 112) received the LA hint system as introduced above. Participants in condition B (n = 81) received a non-LA static hint system. For this condition, instead of receiving the LA hints that are real-time and tailored, the hints delivered are static and were presented to students altogether as a list of bulletin points (see Figure 3). Participants in condition B were given the choice on when to open the hint box and which hint to read all by themselves. The hints delivered to conditions A and B contain the same set of hint messages, the main difference is whether the hints were delivered via LA techniques or as static bulletin points. Condition C (n = 92) was a control group that participants did not receive any hints from the environment.

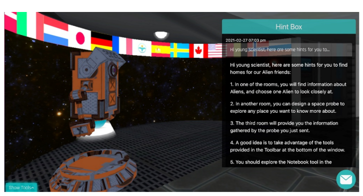

Figure 3: Static System for Condition B

3.4 Data Sources

3.4.1 Student Problem-Solving Performance Score. After students completed the AR activity. Teachers graded students' problem-solving performance following the rubrics provided by AR program developers [19] based on whether the student placed alien correctly and the quality of their rationales for each placement. Only the students who placed all aliens correctly and composed reasonable rationales would be given the full score, which is 100 points.

3.4.2 Student Problem-Solving Self-Efficacy (SE). The scale for measuring students' problem-solving SE was adopted from the Self-Efficacy for Problem-Based Learning Scale (SPBL). This scale is developed by Onan et al. [29] to measure students' beliefs about their ability in solving problems. It includes 18 items with 5-point Likert responses, the Cronbach α reported from this study was 0.92. Although students had similar backgrounds in interacting with virtual PBL environments as reported by teachers, they might have different levels of SE due to diverse prior experiences. Therefore, students were asked to fill out the scale before and after the intervention as pre- and post-test, the pre-test scores were used to reduce the variance brought by prior SE levels.

3.4.3 Student Interviews. 5-6 students were randomly selected from each condition as a focus group to join a 15-minute semi-structured interview at the end of intervention. For students in conditions A and B who received hints, the interview questions are more about whether and how they interacted with the hint systems when solving the problem. Example questions included: "can you provide a scenario to describe how did you take advantage of the hints?" or "after this activity, how do you feel about your confidence in dealing with similar problem-solving activities in the future?" For students in condition C, who did not receive any hints, the questions were related to their experiences in using AR.

All student interviews were transcribed and coded by researchers. The coding process (data reduction, data display, conclusion drawing, verification) was guided by the framework proposed by Miles et al. [28], and the coding methods such as selective or axial coding techniques were applied [6]. The coding process was performed iteratively by researchers to ensure trustworthiness until 100% inter-rater reliability was achieved.

3.4.4 Student-Generated Log Data & Preprocessing. The total of 678139 lines student-generated quantitative log data was collected. It contains student ID, timestamp including start time and end time (by second), the name of accessed features, and actions such as click or select.

According to previous research about PBL [11], a thorough PBL activity usually consists of multiple steps including Identify Facts (IF), Generate Hypothesis (GH), Identify Knowledge Deficiencies (IKD), Apply New Knowledge to Generate Solutions (GS). Learners perform the steps iteratively or in different order until solutions are generated. To better understand students' problem-solving patterns in AR, student logs were mapped into four problem-solving steps adopted from the PBL cycle proposed by Hmelo-Silver [11]. Table 1 present an example of the mapping outcomes. The first PBL step involves activities students performed to understand the problem scenario. AR provides a series of tools such as *Solar System* or *Concept Database* for students to collect various types of needed information, thus, the access to these tools aligns with the idea of IF. Students will generate possible solution hypotheses as they gathered more information, the probe-sending feature in AR is an important feature that allows students to actively obtain information to narrow down and generate hypotheses, thus, the actions related to sending probes were mapped under GH. Moreover, AR provided students with a tool called *Notebook* to organize obtained information and then identify the piece that are still needed, which resonates with the step of IKD. Plus, the *Notebook* also assists students to produce possible solutions via a *Comparing Notes* feature, which allows students to conveniently compare the information they gathered about planets and aliens' needs to decide which place is habitable for which alien, in this case, actions relevant to comparing notes were mapped under GS. In all, mapping the raw log data into higher-level PBL steps allows the interpretation of problem-solving behaviors to be more informative and be supported by a theoretical foundation [5].

Eventually, log data were transformed into 4874 lines of sequences that reflect students' entire problem-solving path by day. Table 2 presents an example of processed sequences, the number in the sequences are the index of PBL steps as indicated in Table 1. For instance, the first row indicates the activity sequence of student 1 on Apr.23rd is IF, IKD, GH, IF, GS. These sequences were then used for sequential analysis to examine student problem-solving patterns across three conditions.

In AR, students also need to compose a series of statements to justify their problem-solving behaviors. The qualitative log data include 1268 statements students composed during the activity when sending probes to search for useful information, each student produced 6 statements on average. To send probes and state the purpose of probes is a crucial step especially in the latter part of AR activity to figure out feasible solutions. The contents of these statements reflect students' plans for the solution finding and their engagement during the activity. To process the statements, researchers coded all statements using the framework designed for evaluating middle school students' scientific inquiry and argumentation skills [25, 32]. The coding and triangulation process followed the same steps of the aforementioned interview coding procedures, 100% inter-rater reliability was achieved too. In sum, all statements were coded into four types based on their robustness of claims, inquiries, and rationales (see Table 3), the quality of the statements increases as the type moves from *Random* to *Reasoning*. This qualitative log data provided another aspect of information to understand students' problem-solving behaviors during the process.

In all, this study applied a sequential explanatory mixed-method design. It consists of first collecting quantitative data, which is the student problem-solving performance and problem-solving SE scores, to examine the intervention effects. Then analyzed qualitative student interview transcripts to help explain and elaborate on the quantitative results [7]. Meanwhile, since log data was collected in a real-time manner, which mirrors students' problem-solving behaviors throughout the entire process [20]. The log data was examined to provide process-oriented information in understanding students' different problem-solving behaviors across the conditions that could be impacted by the hint systems.

4 RESULTS

4.1 Effects on Problem-Solving Performance

To examine the effects of different hint conditions on students' problem-solving performance, a one-way analysis of variance (ANOVA) was conducted on the students' problem-solving performance scores with the three conditions as the independent variable. The results showed a significant main effect, $F(3,285) = 4.54$, $p < .05$. Post hoc analyses using the Bonferroni adjustment for significance indicated that the average score of condition C ($M = 63.16$), which is the control group, is significantly lower than the other two conditions. While the effect is similar between condition A ($M = 74.83$), which received LA hints, and condition B ($M = 74.20$), which received static hint system (see Table 4). This result indicated that students' performance in problem-solving activities could be improved either with the support of LA or static hint systems.

In terms of how did the hint systems affect students' problem-solving behaviors, two themes (*Provide guidance*, *Provide explanation*) emerged from student interviews in both conditions A and B (see Table 5). The results revealed that the hint systems in both conditions provided similar kinds of assists during the problem-solving process, which might explain the similar effects on problem-solving performance between the two conditions. For example, a student in condition A mentioned that "it just kind of guided me for what I am supposed to do, I thought it was useful" and a student in condition B recalled that "I feel like reading thorough those hints were really helpful just to get like starting information." Besides, students in both conditions expressed that the hint systems assisted their solving process by providing explanations about tools and features in AR. For instance, a condition A student said, "I didn't know what it (a specific tool in AR) was, and it explained to me what it was and helped me to help the aliens", which resonates to a statement provided by a condition B student: "I think it is good instruction, I like how it tells to how to use Notebook."

Despite the similar effects of the two types of hint systems between conditions A and B, when students in condition B were asked about how can researchers make the hint box more helpful for them, almost all students expressed that they wished the hint system could be more automatic. For instance, a student in condition B said that they hope the hints could "pops up whenever you are progressing the game. It helps, and get more hints as you go" and another student suggested that "let hint box tell you what specifically this room is when you are in the room instead of you click. Because someone might not know what it (hint box) does and be afraid to use it." This outcome indicated that students were expecting to have pop-up hints as the LA hint system does. In fact, the LA hint system did impact students, which will be demonstrated in the following section.

4.2 Effects on Problem-Solving SE

To examine the effects of different hint conditions on students' problem-solving SE, a one-way ANCOVA was conducted to determine the difference between the conditions on students' problem-solving SE post-test scores, while controlling for students' pre-test problem-solving SE scores. The result showed a significant main effect, $F(3,285) = 3.69$, $p < .05$. Post hoc analyses using the Bonferroni adjustment for significance indicated that the improvements of condition A, which applied the learning analytics hint system, is significantly higher than the other two conditions. The effects is similar between condition B, which received static hints, and condition C, the control group (see Table 6). This result indicated that the LA hint system is effective in improving students' self-efficacy in problem-solving activities than the static hint system and no hint condition.

In terms of how did the LA hint system affect students problem-solving SE, other than the two themes indicated in Table 5, two unique themes (*Provided real-time supports*, *Provided in-time positive feedback*) emerged solely from the interviews of condition A, which could explain the significant higher SE of this condition (see Table 7).

Table 1: Mapping of Raw Logs to Higher-level PBL Steps

Example Log Activities in AR	Steps in PBL	Definition
Alien Database: Click Concept Database: Click Solar Database: Click	Identify Facts (IF, index = 1)	Students identify the relevant facts from the environment, which helps them to represent the problem.
Probe Design: Change ProbeName Probe Design: Click Mission Control: Click Instrument	Generate Hypothesis (GH, index = 2)	Students take initiatives to generate possible hypotheses as understand the problem better.
Notebook: Click Notebook: Create Notebook: Edit	Identify Knowledge Deficiencies (IKD, index = 3)	Students identify the gained knowledge against to knowledge that is still needed.
Notebook: Compare Notebook: Drag Notebook: Drop	Apply New Knowledge to Generate Solutions (GS, index = 4)	Students use the obtained knowledge to produce solutions.

Table 2: Example of Processed Sequences

Student ID	Date	Activity Sequences
Student 1	4/23/2021	[1, 3, 2, 1, 4]
Student 1	4/26/2021	[1, 3, 1, 3, 1, 4, 1, 1, 1, 3, 1, 1, 1, 1, 4, 1]
Student 2	4/27/2021	[1, 1, 2, 1, 3, 1, 1, 3, 1, 2, 1, 3, 1, 3, 1, 3, 1, 2, 3]

Table 3: Codebook for Probe-Sending Rationale

Type	Definition	Examples
Random	Random input. Indicating students' aimless or disengaged behaviors.	(1) oyjunhbgtrvfsxa. (2) hello world.
General Claim	An inquiry was presented without details. Indicating students' exploratory behavior in figuring out the purpose of the PBL environment.	(1) learn more about it. (2) SAVE ALIENS.
Specific Inquiry	An Inquiry was presented with specific inquiry details. Indicating students' behavior in figuring out feasible solutions.	(1) to find information on jupiter. (2) I need the surface, magnetism, and seismic activity.
Reasoning	A reasoning statement was clearly illustrated by connecting evidence to claims. Indicating students' proficiency in understanding and handling this problem-solving scenario.	(1) Because I want to know more about Charon since it is one of the farthest moons in our solar system. (2) I believe that the Akona should live on Triton, but I need to make sure. I need to see if there is any seismic activity, and if the surface is suitable for the Akona.

Table 4: Differences in Means for the Student Problem-Solving Performance Scores

Contrast	Mean Difference	*SE*	95% Confidence Interval
Condition A versus Condition B	.63	4.00	-9.03, 10.29
Condition A versus Condition C	11.67*	4.14	1.67, 21.68
Condition B versus Condition C	11.04*	4.45	.31, 21.78

In AR environment, students need to manage a series of smaller tasks or problems, such as how to send probes or how to use *Notebook* tool, to figure out solutions. Each time when students in condition A tackle a small task, relevant hints would pop up to facilitate their actions. According to Bandura [1], one of the major sources of SE is previous mastery experiences. This LA hint system was assisting students in real-time when they were proceeding through

Table 5: Themes Emerged for RQ1

Theme	Definition	Example Quotes
Provided guidance	The hint system provide students with some basic information to inform their problem-solving	Condition A: the hint box kind like guided me whenever I went off track and it helped meme like find my back and told me what to next. Condition B: it is helpful because I didn't know what to do after that, and I figured it out because of the hint box.
Provided explanation	The hint system provide students with explanations about tools and features in AR	Condition A: I like how it says which room is which, because sometimes I got mixed up. Condition B: when I open the hint box, it also gives you the description about each of the rooms. So the hint help you with that too.

Table 6: Differences in Means for the Student Problem-Solving SE Scores

Contrast	Mean Difference	*SE*	95% Confidence Interval
Condition A versus Condition B	3.23*	1.31	.09, 6.38
Condition A versus Condition C	2.87*	1.36	.20, 5.55
Condition B versus Condition C	.36	1.40	-2.40, 3.12

Table 7: Themes Emerged for RQ2

Theme	Definition	Example Quotes
Provided real-time supports	The hint system provide students with real-time supports that align with students' problem-solving progress.	(1) whenever I got stuck, it kind useful. (2) It helped me because when I first logged in, I really didn't know what to do and how to do it. It told me talk to the robot, it got like helped me got introduced to the game.
Provided in-time positive feedback	The system provide students with positive feedback like emotional support when students solved a small task.	(1) I sort of surprised when I see the hint popped up. (2) I like it just over the time, when we ever do something right or wrong, it just pops up and show us what to do next.

a series of small tasks to ultimately solve the problem in AR. For example, a student mentioned: "at the beginning, it kind helped me like to figure out where I'm gonna be doing. And then, when I am about to do probes, one popped up saying like, explaining the probes kind of, and it helped me with that." Plus, every time when students completed a small task, the pop-up hints also provided positive feedback that confirms the action and encourages students to proceed. As a student said, when he read the pop-up hint, "it does feel like rewarding once you did something." The positive feedback students gained brings a mastery experience that could fuel their problem-solving SE, or, their belief about their ability in problem-solving. Then, this belief would be employed to manage the following tasks until students figure out the final solutions. This entire process can be seen as a journey of students gradually building up their SE task by task, which explains the significant increase of problem-solving SE for condition A students. While students in condition B lack such experiences, even though they could access the hint box during the activity, not everyone would recognize and utilize the most suitable one from a list of hints to tackle the specific task at hand. Their problem-solving progress were less smooth than their peers in condition A and their flow experiences in solving problems would be disturbed [18], this experience might ultimately affected their post SE after problem-solving activity [12, 26]. Therefore, the real-time supports and in-time positive feedback delivered by LA hint system could contribute to the significant improvement of problem-solving SE.

4.3 Problem-solving patterns revealed by Logs

4.3.1 Student-Generated Quantitative Log Data. To answer the third question, student-generated quantitative and qualitative log data were processed to examine students' problem-solving patterns. For the quantitative log data, Sankey graphs were generated to represent students' sequential problem-solving patterns. Sankey graph was selected because it can visualize the iterative manner of students' problem-solving steps [11]. Besides, it also presents the strength of each sequential path–the wider the path between two steps, the larger proportion of the sequential activity between these two steps among all sequences in the graph. Figure 4 presents the overall problem-solving sequential patterns, each column of graphs present a condition respectively. The three graphs in the upper row are the patterns that show students' sequential paths in the first half of AR activity (first 5 class sessions); the three graphs below represent the pattern in the latter half of the activity (latter 5 class sessions). Demonstrating these graphs with the first and latter half separately could provide more information to interpret students' problem-solving patterns within the process since students won't reach certain steps like *Generate Solutions* until the latter half of the activity. Thus, separating each condition into two halves can exhibit more nuanced differences across conditions.

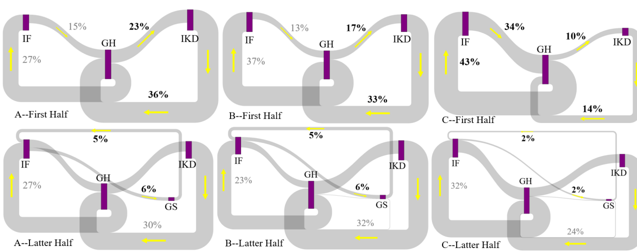

Figure 4: Problem-Solving Sequential Patterns for All Conditions
Note. IF = Identify Facts; GH = Generate Hypothesis; IDK = Identify Knowledge Deficiencies
GS = Apply New Knowledge to Generate Solutions

For the three upper graphs that represent students' first half of problem-solving patterns, a notable difference appeared in the graph of condition C. Compared to conditions A and B, students in condition C conducted a smaller proportion of sequential activities going back and forth between GH and IKD (10%, 14%) while a larger proportion IF and GH (34%, 43%). This finding indicates that, without the supports of hint systems, students in condition C were more likely to generate hypotheses directly after identifying some fact (ID) from the contents (34%), and then went back to the contents again (43%). While their peers in conditions A and B were less likely to generate hypotheses right after viewing the contents, instead, they generated hypotheses mostly after they identified knowledge deficiencies, particularly for students in condition A (36%). Based on the PBL steps [11], a solid hypothesis is built upon students' careful examination of obtained information, a hypothesis generated after the recognition of knowledge deficiency would be more robust than those simply drew from viewing the contents (IF). In this case, the three upper graphs indicate that in the first half of activity, the hint systems did support students in conditions A and B to be in a better position to generate hypothesis since a larger proportion of actions were made after students figured out what information they already have and what are yet to be gathered.

As to the three lower graphs that represent students' latter half problem-solving patterns, a finding is that students in condition C conducted a smaller proportion of sequential activities between IF and GS (2%, 2%) than their peers in other conditions. In AR, the activities aligned with GS step are a series of actions about the *Comparing Notes* feature. This feature allows students to place planet conditions and aliens' needs side by side to determine which alien could be matched to what planet. The wider paths between IF and GS of conditions A (5%, 6%) and B (5%, 6%) indicate these students often went back to the contents to check out some information when they were composing the solution and rationale for each placement. A possible reason can be that one of the hint messages contains a reminder for students to check key contents before submitting the final solution. It turns out some students in conditions A and B followed the hint, which means the hint systems did impact students' problem-solving patterns during the process of composing final solutions.

Overall, as indicated in Figure 4, although there are minor differences between sequential patterns of students in conditions A and B, while the patterns condition C shows a more salient difference. This outcome resonates with the findings of students' PBL performance reflected in RQ1, and also demonstrates LA's role in providing in-depth and nuanced demonstration about learner behaviors during the process.

4.3.2 Student-Generated Qualitative Log Data. For the qualitative log data, figure 5 shows the proportion of the rationale types across three conditions. Although the *General Claim* occupies the largest proportion in all conditions, two interesting findings emerged. Firstly, there is more *Specific Inquiry* in condition A (27.80%) compared to conditions B (17.95%) and C (16.51%). Secondly, more *Random* emerged in condition C (15.07%) compared to conditions A (8.96%) and B (8.97%), while no salient differences on *Reasoning* and *General Claim* are revealed. These results show that students who received LA hints composed the rationales with more solid evidence and inquiries than students who received static hints or no hints, whereas more randomly-typed sentences were found in condition C than the other groups.

To interpret these outcomes, firstly, it takes time and effort for students to compose a higher-level statement like *Specific Inquiry*. Secondly, PBL is a student-centered activity that students are working in a self-directed manner. In order to produce higher-level statements, students are expected to be engaged and to have a positive attitude towards the activity. The outcome that students in condition A composed a larger proportion of *Specific Inquiry* whereas students in condition C produced more lower-level *Random* could indicate students who received hints, especially the LA hints in condition A, were undergoing a healthier learning experiences than students in condition C. It echoes the finding revealed from RQ2 about problem-solving SE. SE is a belief that reflects students' confidence and emotions toward an activity [1], it also associates with students' engagement and attitude during the process [21]. Thus, the qualitative log data provided evidence that aligns with the beneficial impacts of LA hints system on students' problem-solving SE.

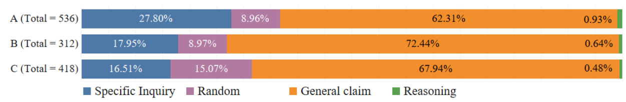

Figure 5: Proportions of Statements Across Conditions

5 DISCUSSION & IMPLICATIONS

5.1 Impacts of LA Hint System on Problem-Solving SE

Statistical results showed that the problem-solving SE for students who engaged with LA hint system has improved significantly. Students indicated in the interviews that except for receiving guidance and explanation from the hint system, the real-time problem-solving supports and in-time positive feedback are the key benefits that are superior to the static version. The findings proved that the real-time assistance brought by LA hint system was acknowledged and appreciated by students, and in return, it improved students' belief about their ability in solving problems in science class. The analysis of student-generated statements also confirmed the improvement of SE. Students who received hints especially with LA hints were more engaged when they were composing statements for sending probes to gather needed information, and they provided detailed evidence and claims that made their rationale have higher quality. For students who received static hints or no hints that lack real-time supports, it requests them to own higher resilience to keep themselves engaged in such a self-directed learning environment [15]. Without in-time and tailored support as well as feedback, it is harder for them to keep themselves engaged in the student-centered activity especially when the participants are in middle school level, which ultimately impacted their gaining on problem-solving SE.

More importantly, LA hint system provided researchers and educators an opportunity to handle the challenges (ill-structured problem, student-centered learning) for implementing PBL at middle school level. It could foster a healthy self-directed learning environment that (1) supports students to tackle the complex ill-structured problem by providing in-time supports and (2) eases students' stress when transiting to the student-centered activity by providing in-time positive feedback. The entire process of the activity allows students to learn and gain SE gradually along the way.

5.2 The Role of Quantitative and Qualitative Log Data

This study presented the advantage of user-generated log data in understanding empirical outcomes. More specifically, the quantitative log is beneficial in explaining the behaviors during the sequential activity, whereas psychological measures were better interpreted with qualitative log data.

Although the effects of hint systems on problem-solving performance between conditions A and B were similar. Quantitative log data enabled researchers to examine the problem-solving pattern closely between the two groups and it did reveal nuanced difference on problem-solving sequential patterns. The complied behavioral data provided researchers and educators a more comprehensive perspective about the effects of implementing hint systems in virtual PBL environments.

Moreover, given previous LA studies indicated the limits of reflecting learner psychological factors by using quantitative behavior logs [10]. In fact, the use of qualitative log data in this study can be a promising approach to interpreting the outcomes of psychological measures. The analysis of students' statements provided information to triangulate and supplement the interpretation of statistical findings, which circumvent the pitfall of using quantitative behavioral logs to mirror innate psychical measures [14].

In general, by integrating multiple types of data sources, this study presented that performance, self-report, interviews, and log data could be weaved together to interpret and analyze empirical outcomes.

5.3 Implications for Future Practice

The study also provided implications for future LA hints system employment. When students in condition C were asked about the aids they wished to have when solving the problem, students mentioned in the interview that they hoped to have some supports like hints. As one student said, "if you get stuck on it, the hint could really help. It (hint) doesn't give you the answer but direct you towards it". This finding implies students were expecting more supports during virtual PBL activities, which indicates the necessity of introducing hint systems, especially LA hint systems to virtual PBL environments for the middle school level.

Moreover, students in condition B indicated that their teacher always reminded them to check the hint box before they asking for help. Teachers' frequent reminders about the hint box might have the impacts similar to pop-up hints, especially when students happened to encounter difficulties. This could be one of the reasons for the similar problem-solving performance outcomes between conditions A and B. In other words, if students with static hint systems were left with full control over the hint box without teachers' reminders, the outcomes of their performance might be different, which points out a possible future research direction.

6 CONCLUSION

The study showed that the LA hint system improved students' problem-solving SE significantly. Student interviews indicated that it is the real-time supports and in-time positive feedback delivered from the LA system that facilitated students' SE growth. Although the effects of PBL performance were similar between conditions A and B, the quantitative logs revealed that students' problem-solving patterns were still impacted by the hints systems. Qualitative logs also revealed traces of positive learning experiences after students engaged with the LA hint system. In all, the research outcomes presented the promising role of LA hint system in supporting virtual PBL activities and also provided implications for integrating quantitative, qualitative, and log data to examine the effects of apply LA incorporated educational tools.

A APPENDICES

Log Actions	Message
Once students entered the scene	Hi young scientist, this is your Hint box, you will receive hints every now and then for you to find homes for our Alien friends. To help you start with, your first hint is: There is one room in this space station that provides all information about our Alien friends, you should check it out and learn about what they need.
Students accessed Alien DB first time + Stayed longer than 17s + Students left Alien DB	Well done! You unlocked another hint: There is a Toolbar at the bottom of the screen. It has the tools you can use to help our Alien friends.
Students accessed Alien DB first time + Stayed less than 17s + Students left Alien DB	Hint! To learn about Alien's needs is very important for you to help them, it will be great if you can learn about at least one of our Alien friends. After you do that, then you can also check out the Toolbar at the bottom of the screen. Those are the tools you can use to help our Alien friends.
Students accessed Notebook Tool + Students accessed the Compare Note feature + Students closed Notebook tool	Great job exploring the Notebook, and you just unlocked another hint: A good idea is to help our Alien friends one by one instead of helping them all at once.
Students accessed Notebook Tool + Students did not accessed the Compare Note feature + Students closed Notebook tool	Hint! The Notebook tool is very useful, especially the Compare Notes feature in it, you should definitely give it a try if you haven't! After you explored everything in Notebook, please go ahead to help our Alien friends. A good idea is to help them one by one instead of helping them all at once.

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