A Plant Simulation Tool for Collaborative Biology Experiments in Middle-school Classrooms: An In-the-wild Study

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ABSTRACT

Computer-aided simulation-based platforms have been shown to be effective tools for teaching STEM concepts. At the same time, Computer Supported Collaborative Learning (CSCL) platforms encourage different viewpoints and approaches from the learners which can enrich the learning experience in STEM classrooms. The deployment in recent years of networked personal devices such as Chromebooks in classrooms has motivated educators to design collaborative learning tools for these devices. However, prior work has shown that using one-on-one devices may discourage students from talking among each other, which hinders collaboration. To understand the affordances of personal devices for CSCL tools within Biology curricula, we designed a collaborative plant growth simulation application that provides mirrored plant growth simulation views for every group member to facilitate a common visualization. In this paper, we present our findings from an in-the-wild study that evaluated the affordance and usability of the plant growth simulation application and investigated the nature of collaboration and engagement aided through the simulation mirroring feature. Our study results showed that the plant simulation application had high usability and acceptance. Moreover, mirroring the plant growth simulation improved collaboration, generated excitement, and stimulated conversation. We also identified episodes where collaboration was hindered due to off-task activities, troubleshooting, group dynamics, and lack of understanding that led us to outline some potential guidelines to improve the collaborative learning experience for the students in Biology classroom.

CCS CONCEPTS

• **Human-centred computing** → Collaborative and social computing; Collaborative and social computing theory, concepts, and paradigms; Computer supported collaborative work..

KEYWORDS

Collaborative learning, Computer Supported Collaborative Learning, CSCL, classroom learning, middle school STEM education, Biology curriculum, collaborative simulation, Biology simulation, plant growth simulation, multi-device platform, cross-device interaction, in-the-wild classroom study

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1 INTRODUCTION

Knowledge about living systems, plant processes, and energy transformation in plants is crucial for understanding the complex issues related to environmental sustainability and solving bio-engineering problems, such as ensuring sustainable food production and protecting the environment for living organisms [18, 33]. Engaging students in science investigations that include learning from hands-on experiments can enhance students' learning experiences within STEM curricula [9, 10, 19, 22, 32]. Unlike many other STEM subjects, experiments from Biology curriculum often have requirements such as larger space, longer time, specific climate (e.g., growing plants in winter in northern Canada), and controlled environment (e.g., growing plants in a greenhouse) that are not always feasible in normal classroom contexts. Incorporating Computer Supported Collaborative Learning (CSCL) tools in Biology classrooms can support mimicking real-world Biology experiments to help students learn the desired content, as well as overcome the limitations of time, space, and climate requirements for Biology experiments to unfold [4, 8, 15, 20]. Moreover, collaborative learning supported by such CSCL tools can help middle-school students gain diverse perspectives on the subject matter, helping them improve their problem-solving skills, learning motivation, and overall attitude towards science [2, 14, 19, 27, 36, 43, 45, 53].

To get the best outcomes from a collaborative STEM lesson, it is important to combine both individual and collaborative classroom activities [11, 28]. The key challenge for designing an effective CSCL tool for STEM curricula is to provide seamless information flow and uninterrupted transitions between those individual and collaborative learning activities [11, 23, 26]. As many schools are using personal-use devices such as Chromebooks in classrooms, educators are becoming more interested in designing CSCL tools for those devices [56]. While there are many advantages to having students work on individual devices to support CSCL, Fleck et al. [17] observed that when students use one-to-one devices, they may talk less with one another as they perform group activities, and, instead, focus on their own screens and trials to work individually, or dictate the course of the collaborative learning activities. Such behavior can hinder the balance, information flow, and seamless transition between individual and collaborative activities that can limit the benefits of collaborative learning.

This observation that individual devices lead to less collaboration and discussion prompted us to create a CSCL tool within Biology curricula for Chromebooks – a plant growth simulation application for middle-school children to learn how environmental factors impact the growth of different plants. When working on the collaborative learning activities (i.e., running plant growth simulation experiments in groups with their given amount of temperature or water), multiple students could work simultaneously on their individual devices, while mirroring the plant growth simulation view with everyone, instead of running individual plant growth simulations on their own devices. Mirroring the plant simulation across group members creates an opportunity for uninterrupted information flow and knowledge construction during collaborative activities. At the same time, having individual control to other application components (e.g., post-simulation plant inspection) facilitates individual learning.

We evaluated our plant growth simulation application in an in-the-wild study that was part of a six-day long Biology curriculum. We ran this study with forty-three eighth-grade students from two classrooms, who conducted plant growth experiments with our plant simulation application in real classrooms, to answer the following research questions:

RQ 1. (a) Which features of the Plant Growth Simulation application enhance the usability of the system in both individual and group work? (b) What types of difficulties do middle-school students encounter when they interact with the Plant Growth Simulation application?

RQ2: What kinds of collaboration and engagement are supported by a plant Biology simulation application that enables real-time collaboration between group members through a mirrored plant simulation approach?

The plant growth simulation application received overall very positive usability ratings from the students. The features related to the mirrored plant growth simulation view, the input and output information, and the 3D plant view were very useful to understand the impact of temperature and water on different plants. Our study results demonstrated that the mirrored plant growth simulation feature of the collaborative plant simulation application helped in generating discussion, excitement, and engagement in a group setting. Group members collaborated and coordinated on planning and running the experiments to achieve a common goal; thus, the application facilitated CSCL to enhance students' classroom learning experiences. We also observed a few times students opted to work individually or went off-the-track. Our analysis identified reasons (e.g., group dynamics, software glitches, lack of interest, etc.) behind such behavior. Based on our analysis, we recommend some potential design guidelines, for example, limit the creation of a new plant simulation trial when someone is already working on running a trial to avoid system overloading. Moreover, adding effective sorting features for the previous simulation trial information view to ensure seamless information flow from previous activities to the current one to help improving the usability and acceptability of the system. Creating more opportunities with appealing concurrent activities for everyone in the group, such as gamification can improve collaboration in the CSCL platforms for Biology curriculum.

2 RELATED WORK

2.1 Computer Supported Classroom Learning (CSCL) Technologies

Compared to traditional classrooms without modern technologies, Computer Supported Classroom Learning (CSCL) provides students with diverse ways to communicate and share information towards better facilitating the learning process [34, 45]. Technologies such as tabletops and large-screen smart whiteboards have been extensively researched and have been found to facilitate face-to-face collaborative learning by supporting group interactions and learning in a shared physical space [3, 6, 12, 14, 16, 23, 41, 46]. Collaboration among students on interactive tabletops can be instigated by physical and verbal communications [31]. Children exhibit high levels of social play and group formation, transitioning from individual agency to collective agency within the CSCL environment

[24]. While CSCL is more effective when it facilitates a balance between individual and collaborative learning activities, prior work has found that it is challenging to maintain that balance [28]. Some prior CSCL technologies designed around large tabletops showed that they limited the scope of individual learning [1, 3, 8]. Platforms designed around a shared workspace are often distracting to students due to the constant presence of a shared workspace, hindering in-depth individual learning mechanisms [22, 24, 28].

Even though there are many studies about tabletops, large screens, or multi-screens for collaborative learning, CSCL technologies designed around personal devices remain comparatively under-explored. A comparison study among personal devices showed that students engage more with laptops than smartphones in a collaborative classroom setting [1]. Another prior study that investigated the integration of multi-screen technologies in a K-12 classroom found that the use of large projected displays, small touch surfaces, and students' physical location within the classroom facilitated new forms of learning and interaction, leading to improved student collaboration and understanding [52]. Personal devices that are equipped with groupware platforms like Google Classroom can support both individual and collaborative learning as well as affordability and data autonomy [35], which makes it a prominent choice in schools. One limitation of using personal device supported CSCL is that such platforms provide no explicit support for a shared workspace for collaborative learning activities. That can cause some students to choose work individually, dominate the group activity, or limit other group members' participation, which can limit the scope of collaboration [17].

2.2 Simulation Tools for School Biology Curriculum

Simulation tools to learn Biology curriculum in schools can reduce the cost of building Biology labs that often require larger space and controlled environments [43]. Moreover, learning Biology curriculum with simulation tools can motivate students to understand the important features and variables during their experiments because simulation tools create opportunities for learning from repeating the same experiment multiple times with minimum time and cost, compared to learning from real-life Biology lab experiments. Even though knowledge of life sciences is fundamental, students' biological understanding is an under-researched area [49]. Biology related topics that are taught from elementary school to high school through simulations are as diverse as introductory biology, enzymatic reactions, anatomical structures, genetics, molecular chemical representation, molecular biology, cell biology, population dynamics, biotechnology, biochemistry, diffusion and osmosis, and frog dissection [8, 21, 25, 30, 37, 39, 43, 44, 48, 54, 55]. However, prior studies highlighted that there are far fewer biology-related simulation tools that are deployed in schools in comparison to simulations in other areas of science, such as physics and chemistry [54, 55].

Prior research showed that learning from Biology simulation tools improved students' understanding of the subject matter that reflected on their test scores, compared to students who learned from traditional textbooks and other supplementary materials [21, 25, 30, 39, 48]. Using computer-supported simulation tools for Biology experiments promoted more critical thinking, scientific knowledge processing skills, and conceptual growth in students, compared to students who did not use any simulation tools [8, 21, 37, 44, 54, 55]. Moreover, computer-supported simulation tools increased students' motivation, confidence, and attitudes toward Biology curriculum [8, 54]. Some prior studies found that students preferred computer-supported simulation tools to learn Biology curriculum over learning from textbooks or physical lab experiments [39, 48].

These simulation tools to learn Biology are mostly designed for individual learning on individual student's devices [8, 21, 37, 39, 43, 44, 48, 54, 55], with a few exceptions of running simulations in a shared computer or a microcomputer by a group of students [25, 30]. Although this prior research investigated real classroom settings around simulations in Biology using personal devices in the classroom, less is known about collaborative real-time Biology simulation tools enabling group members to synchronously view each other's interactions when sharing a view of the simulation.

3 COLLABORATIVE PLANT GROWTH SIMULATION APPLICATION

We created a collaborative plant growth simulation application to teach the impact of environmental factors such as temperature and water on the growth of three different types of plants (i.e., tomato, bell pepper, and watermelon). The application was extended from our prior works [47, 50] that facilitated plant growth simulation for only the tomato-temperature combination. We also improved the simulation application based on the findings from our prior controlled laboratory study with middle-school children [47]. In this application, students run individual or group plant simulation experiments by entering the temperature or water amount for a selected plant to see how that plant grows in that given temperature or water amount. In case of group experiments, all group members view the same plant growth simulation with the same plant-factor combination and factor input amount that is generated by one of their group members.

3.1 User Interface

The plant simulation application user interface has two tabs: (1) simulation tab and (2) trials tab.

3.1.1 Simulation Tab. The *Simulation* tab (Figure 1) has two main functionalities: (1) create a new group or join an existing group if they want to run a plant growth simulation collaboratively and (2) run a plant growth simulation either individually or in a group by selecting a plant-factor combination from a list of pre-existing plants and factors.

Create or Join a Group. If students want to run plant growth simulation experiments in a group, they need to first use the *Possible Friends* menu from the simulation tab (Figure 1) to create a new group with their team members or join an existing group that is already created by one of their group members. Selecting the *Possible Friends* menu provides two lists: *Free Friends* and *Groups of Friends* (Figure 2). To create a new group, students click on the *Free Friends* list and select their group members from a list of available students who are not currently in a group and click on the *Connect* button (Figure 2). Multiple students can be added at the same time

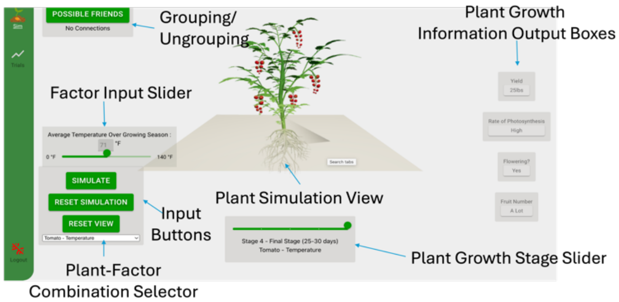

Figure 1: The simulation tab of the plant growth simulation application. The grouping menu, the factor input slider, the plant-factor selection menu are at the top-left, middle-left, and bottom-left corner of the screen, respectively. The mirrored plant simulation view along with the plant growth slider are at the centre of the screen. The simulation information text output boxes are at the right side of the screen.

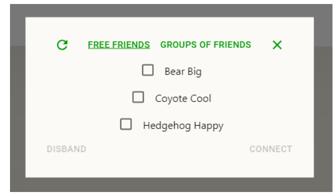

Figure 2: Create a new group with available students from the *Free Friends* list.

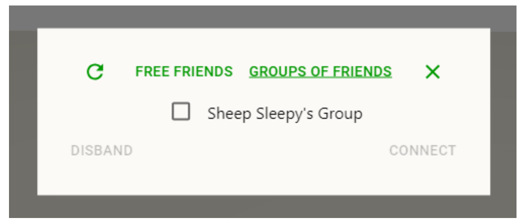

Figure 3: Join an existing group from the *Groups of Friends* list.

from the *Free Friends* list. To join a group, students select the *Groups of Friends* list to find a list of all existing groups to join (Figure 3). Students can select only one group from the list before selecting the *Connect* button. If any student wants to run the plant simulation experiments individually, they can skip this step.

Run a Plant Growth Simulation Individually. To run a plant growth simulation individually, students first need to select a plant-factor combination from the *plant-factor drop-down menu* and then select the temperature or water amount from the *factor input slider* (Figure 1). Clicking the *Simulate* button initiates running the plant growth simulation for that selected plant (tomato, bell pepper, or watermelon) and factor (temperature or water) amount. The plant growth simulation shows a visual representation of the plant's growth across five stages: pre-germination, seeding, vegetative, budding/flowering, and final stage, based on their selected amount of temperature or water (Figure 4). As the simulation proceeds, the *plant growth stage slider* displays the current stage of plant growth (from pre-germination to final stage). Upon completion of a simulation, additional textual information on the plant's health, yield, rate of photosynthesis, number of flowers, and number of fruits are provided in the *plant growth information output boxes* to summarize the impact of the selected amount of temperature or water on that plant's growth (Figure 1). Once the plant simulation is complete, students can click on the *Reset Simulation* button to rewatch the plant growth simulation. They can move the plant growth slider backward and forward to revisit and inspect different plant growth stages. Students can also zoom and rotate the 3D plant model in the simulation view for closer inspection of the plant. Students can return to the original plant view by selecting the *Reset View* button.

Run a Plant Growth Simulation in a Group. Students perform the same steps and interactions as they did in running an individual simulation when they want to run a plant growth simulation in a group. However, once a group is formed by either creating or joining a group, the views of the *plant-factor drop-down menu*, *factor input slider*, *plant growth simulation*, *plant growth stage slider*, and *plant growth information output boxes* are mirrored among the group members. Any interaction initiated by a student that takes place with any of these mirrored components (e.g., moving the *factor input slider* to select the temperature or water) is reflected on every group member's screen such that everyone gets the full advantages of the collaborative experiment with the same visual. If multiple students from the same group try to run a simulation at the same time, the first person who hits the *Simulate* button gains the control of the simulation. The plant growth simulation that runs in that student's device with their selected plant-factor combination and factor amount input is mirrored on the other group members' screens. During an ongoing group simulation, the *factor input slider*, *Simulate* button, and *Reset Simulate* buttons are deactivated to prevent other students from starting a new simulation or restarting the currently running simulation.

To facilitate individual learning experiences in a group mode, the functionalities related to further inspection of the plant growth simulation (e.g., reset the simulation to revisit different plant growth stages, zoom and rotate the plant view for closer inspection of fruits and flowers, etc.) are kept for individual control after completion of a plant growth simulation. This creates opportunities for forming individual conclusions on the plant growth process to bring them to future group discussions, thus creating a diverse view on the subject matter and enriching the collaborative learning experience [28].

3.1.2 Trials Tab. The *Trials* tab consists of a tabular summary of all plant growth simulations that were previously generated by the students, individually or in groups. Students can consult their previous simulation data in the *Trials* tab. The Trials tab control and view is individual even though the student is currently in a group. The reason behind giving individual control and visuals is to facilitate forming individual conclusions from group experiments that can be shared later in the group discussion. Students can select the *plant-factor combination drop-down menu* to see all previous

Figure 4: A plant simulation in five stages: germination, seeding, vegetative, budding/flowering, and final stage.

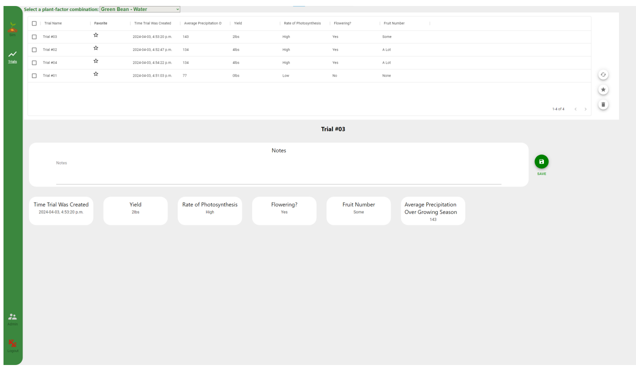

Figure 5: The trials tab of the plant growth simulation application. Each row presents relevant information from a trial.

simulation data from that plant-factor combination. Each row of the simulation tab represents a simulation trial and shows the amount of temperature or water, yield, rate of photosynthesis, number of flowers, and number of fruits for that trial (Figure 5). Students can mark a trial as their favourite and can save additional individual notes on that trial at the bottom of this tab for future group discussions. This helps to stimulate information flow from individual space to collaborative space and enhance collaborative learning.

3.2 Implementation

The plant growth simulation application was developed for Chromebook Flex 5 touchscreen laptops. The user interface was implemented as a web-based interface using JavaScript, React.js, and Three.js libraries. Cross-device interaction used WebSockets servers and was implemented using the RE/Toolkit [5]. The Express.js framework handled the information requests from each student interface. The backend server was built with Node.js. MongoDB was used to implement the database in the backend with the MERN technology stack. All plant (tomato, bell pepper, watermelon)-factor (temperature, water) combination simulation models were generated from agricultural, governmental, and scientific publications with our partners from learning sciences and middle-school curriculum design [47].

4 METHOD

4.1 Participants

We recruited forty-three eighth grade students from two classrooms (classroom 1: $n = 24$ (10M, 14F); classroom 2: $n = 19$ (8M, 11F)) from a Science, Technology, Engineering, Arts, and Mathematics (STEAM) magnet middle-school in the Midwest of the United States that has an ethnically diverse student population and 58% of the students are enrolled in the free or reduced lunch program. In classroom 1, twelve (4M, 8F) students and in classroom 2, eleven (4M, 7F) students gave consent for video and screen recordings. To collect complete collaboration data within a group, these students were placed in the same groups (consisting of 3-4 students) for the tasks. We collected additional data from a post-study Likert-scale type questionnaire from seventeen students from the same classrooms who participated in the study. Additional data from a post-study verbal interview was also collected from the same seventeen students. Our study protocol was approved by the research ethics boards of our three institutions.

4.2 Experiment Setup

Our study took place in two classrooms (hereafter referred to as C1 and C2) that had the same physical layout (Figure 6). We set up GoPro Hero 9 cameras on tripods for each group that gave consent for recording to capture their individual and group activities. These group cameras were pointed towards participants to capture their speech, body language, and physical interaction during their individual activities, collaborative work, and group discussion. We also set up a GoPro camera on a tripod at the right side of the back of the classroom to capture the whole class activities (Figure 6). All students used Chromebook Flex 5 touchscreen laptops that were provided by the school and had already been used in the classrooms to run the plant growth simulation experiments. We used the screen recorders from these Chromebooks to capture students' interactions with the plant growth simulation application.

4.3 Study Procedure and Tasks

Our collaborative plant growth simulation experiment study was a part of a six-day long in-the-wild classroom study that included multiple activities across multiple Biology lessons within a middle-school science curriculum. Students in both classrooms were engaged in the same curriculum. The lessons on understanding the impact of environmental factors on different plants incorporated both individual and group activities where students were instructed to test different plants' growth with multiple trials of different input temperature or water amount using the plant growth simulation application. Among the six days, our plant simulation activities were administered in Days 3 to 5. Each class period was 50-minutes long, except for day 4, which was 35-minutes. In both classrooms, one teacher administered the study, while three researchers observed.

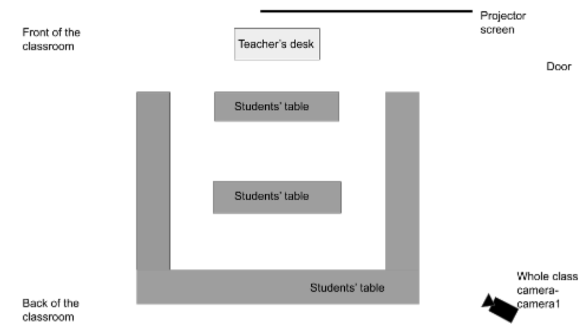

Figure 6: The classroom layout. A projector screen was in front to aid the teacher. A camera was setup to capture the whole-class interaction. Students sat in their tables in groups to do the plant simulation experiments.

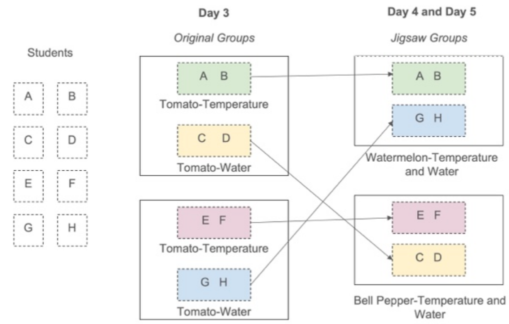

Figure 7: Original and jigsaw group formation. Two members from an original group who worked on the tomato-temperature combination was grouped with two students from another group who worked on the tomato-water combination to form a jigsaw group.

On ***Days 1 and 2***, the curriculum introduced a community garden challenge, prompting students to explore which environmental factors (e.g., temperature, water, light, etc.) contribute to plants' growth with an informal whole class discussion. Activities on these days did not include any plant simulation experiment.

Day 3 class activities were centered around investigations of how two environmental factors, temperature and water, impact tomato plants' growth using the plant simulation application. Students were divided into groups of 3 or 4 to run the plant growth simulation experiments for tomato plants and discuss their findings as a group. Among these groups, C1G1 (Students 106, 114, 117) and C1G2 (Students 105, 107, 124, 126) groups from classroom 1 and C2G1 (Students 207, 218, 223) and C2G2 (Students 214, 217, 225, 228) groups from classroom 2 were recorded. We will refer to these groups as *original groups* in the rest of this paper. Within each group, two students were assigned to find the impact of temperature on tomato plant growth and the other two were assigned to find the same for water (Figure 7). For groups with three members, two of them worked on temperature and one worked on water. At the beginning of this activity, students were instructed to form their individual hypothesis on the minimum, maximum, and ideal range of temperature or water that tomato plants need to survive, followed by a group discussion on their hypothesis. Then, working as a group, students ran multiple trials of tomato plant growth simulations to test their hypotheses with various input values of temperature or water amount. Students were encouraged to keep notes on their findings of the minimum, maximum, and ideal range of temperature or water for tomato plants for future discussions.

Day 4 activities involved testing the impact of both temperature and water on either watermelon or bell pepper plants in a group. At the beginning of Day 4, the teacher reorganized the *original* groups. Two students from a group who analyzed the impact of temperature on tomatoes were grouped with two students from another group who analyzed the impact of water on tomatoes. We will refer to these groups as *jigsaw* groups for the rest of this paper. Jigsaw groups were formed in this way to bring prior knowledge on the impact of temperature or water on tomato plants from different groups, thus bringing diverse viewpoints and collaborative approaches to the table. Among the jigsaw groups, C1G1J (Students 106, 109, 113, 125) and C1G2J (Students 105, 116, 117, 129) groups from classroom 1 and C2G1J (Students 206, 216, 217, 228) and C2G2J (Students 210, 214, 218, 227) from classroom 2 were recorded. On the rest of ***Days 4 and 5***, half of these *jigsaw* groups were assigned to work on maximum, minimum, and ideal range of both temperature and water for watermelon and the remaining half on the same for bell pepper. Students did the same activities for these plants as they did for tomato plants on Day 3.

On ***Day 6***, students discussed their findings on the impact of temperature and water on all three plants with their jigsaw group members, original group members, and whole class, respectively. They reflected on how the same amount of temperature or water is suitable for a plant, but harmful for other plants. They also continued their discussion on general impacts of environmental factors on different plants to plan a community garden. No activities involving the plant simulation experiment were administered. At the end of Day 6, we handed over the students a post-study questionnaire and conducted a verbal group interview to gather additional insight.

4.4 Data Analysis

We collected study data from a post-study questionnaire, a post-study group interview, group activity video recordings, and Chromebook screen recordings to answer our research questions.

Post-study Questionnaire. The post-study questionnaire contained Likert-type scale (1 = Awful, 2 = Not Very Good, 3 = Okay, 4 = Really Good, 5 = Fantastic) data. We replaced the numbers in the questionnaire with smiley faces to make it more appealing to the children [38]. The questionnaire was extended from the system usability scale [7] to investigate the usability related issues of the plant growth simulation application features to answer RQ1. We reported the number of responses in each category (awful to fantastic) for each question.

Post-study Verbal Interview. The post-study verbal interviews were conducted with three groups of students from both classes to understand students' experiences with the interaction of the plant growth simulation application and their collaborative learning experiences. Our interview questions were designed to understand

Table 1: Our coding framework for analyzing interaction, collaboration, and engagement. We extended this framework from [14] and [17].

Collaborative Learning Mechanism for Tablet Framework [17]
Mechanism of Collaborative Discussion and Action
Making suggestions (e.g., verbally and/or physically (with gestures), demonstration, etc.; suggesting ideas).
Accepting suggestions (e.g., listening to and watching others, asking for opinions and clarifications about other's ideas).
Negotiation (e.g., making, watching, and responding to each other's suggestions; disagreeing and suggesting own ideas).
Mechanism for Coordinating Collaborative Discussion and Action
Maintaining joint awareness and attention (e.g., dividing the work to achieve a common goal).
Narration (e.g., verbally dictating course of action).
Intrusion (e.g., invading other's space to complete the task).
Regulation of access (e.g., ensuring own/others visual access to the screen).
Turn Taking (e.g., Taking turn on the devices to physically interact).

Additional Codes for In-the-wild Studies [14]
Non-collaborative interactions (e.g., working independently without any collaboration).
Task work (e.g., Working on the task by one member while others were not engaging).
Off-task interactions (e.g., engaging in other activities, such as playing games and gossiping).
Software conflict (e.g., troubleshooting as a group).

the usability of the plant growth simulation application and to identify any difficulties that the students encountered during the plant simulation experiment (RQ1). The post-study interview data provided additional insight on the quantitative data that we gathered from the post-study questionnaire. The interviews consist of audio data. All interview data was transcribed for analysis using turns of talks as the analysis unit. We followed an inductive coding approach for the interview data analysis. One member from our research team segmented the data, generated codes, and identified recurring themes. The analysis was later verified, discussed, and resolved disagreements with another researcher of our team to reach a consensus.

Group Video Recordings and Individual Screen Recordings. We collected study data from group videos recordings and Chromebook screen recordings to understand if and how the plant simulation application facilitated collaboration and engagement within a group to complete their common tasks (RQ2). Group activity videos allowed us to understand both verbal and physical collaboration and engagement among the group members during the plant simulation tasks. Screen recordings helped us to gain a more nuanced understanding of the affordance and usability related issues of the plant growth simulation application (RQ1), as well as individual and group interactions with the plant simulation application to understand the course of action to complete the collaborative task (RQ2).

All group videos and individual screen recordings were transcribed to gain additional insight. We transcribed these recordings using turns of talks as the analysis unit. At the same time, we captured students' physical interaction and non-verbal communications with the simulation application and their peers of the same group by coding the data while watching the videos and screen recordings. We conducted microlevel data analysis [17] of system and group interactions to understand the common collaboration and coordination patterns that were embedded in the temporal flow of actions. We coded the data both inductively and deductively to capture a variety of interactions occurring in the group collaborative learning. The Collaboration Learning Mechanism (CLM) Framework [17] was applied for the deductive coding, including codes Making Suggestions, Accepting Suggestions, and Negotiations under the Mechanism of Collaborative Discussion and Action, and codes Maintaining Joint Awareness and Attention, Narrations, Intrusion, Regulation of Access, and Turn Taking under the revised Coordinating Collaborative Discussion and Action for tablets coding [17]. Some additional codes, from Evans et al. [14] were added for analyzing the in-the-wild interactions that were not fully incorporated in prior collaborative learning frameworks that were developed from controlled studies [16, 17, 40]. Non-collaborative Interactions, Task work, Off-task Interactions, and Software Conflicts from Evans et al. [14] were applied in our coding deductively. We organized the codes into three categories by adapting the CLM framework (Table 1). Additional codes were added inductively to record our observations from the group video recordings and screen recordings that were relevant to the affordance and usability of the plant growth simulation application.

Four members from our research team analyzed the video and screen recording data along with the transcriptions from eight groups (4 original and 4 jigsaw groups) from the two classrooms. Each of the researchers first viewed and coded group video and screen recording data from two groups (1 original and 1 corresponding jigsaw group), then shared the coding results with other coders, discussed and resolved any disagreement until a consensus was reached.

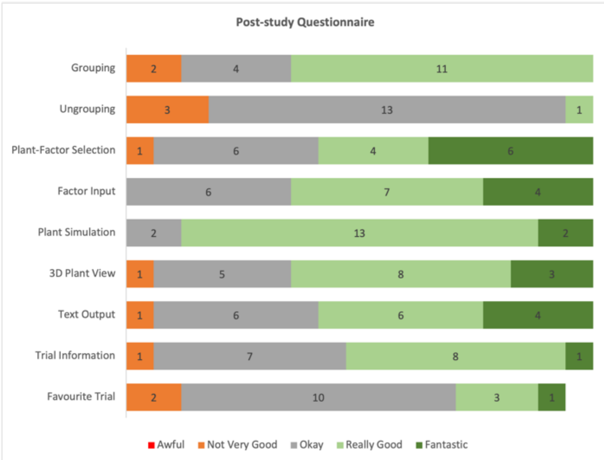

Figure 8: Post-study questionnaire responses (n = 17; one student did not respond to the question about the favourite trial).

5 FINDINGS

5.1 Post-Study Questionnaire

We present the responses from our post-study questionnaire about the plant growth simulation application in Figure 8. Most of the features received positive responses (i.e., *Really Good* or *Fantastic*) from the students. Among all features, the plant simulation view received 15/17 responses with either *Really Good* or *Fantastic*, followed by grouping (11/17), 3D-plant view (11/17), temperature/water input slider (10/17), text output information (10/17), plant-factor section menu (10/17), trial information (9/17) with the same responses. The ungrouping feature (13/17) and marking a trial favourite (10/16) got mostly *Okay* responses. None of these features received predominantly negative responses (i.e., *Not Very Good* or *Awful*) from the students.

5.2 Post-study Verbal Interview

5.2.1 Plant Growth Simulation Application Features. We conducted the post-study verbal interview in three separate groups. We present the students' responses from these groups about their experience with the simulation and trials tab features and their individual and collaborative learning experience.

Simulation Tab. Most of the students expressed that they enjoyed running the plant growth simulation experiment both individually and in groups. Seeing the mirrored plant growth simulation on everyone's screen generated excitement and overall positive attitude towards the plant growth simulation application. Students thought that it was helpful to be able to test with different temperature or water inputs by creating multiple trials and referring to previous trial information. Some students found the ability to control the temperature/water input value to be very useful towards their learning process. Most of them found the plant growth slider to be effective to learn about the different growing stages of the plants after a simulation was completed.

> *"Well, I like how you can like create trials, to like get different results. And you can change the plant, and like the water, the temperature, and see what works best." (Group1)*

> *"I like the temperature one because I can adjust it and see which one works. Instead of just having like this and immediately seeing what the end result is, I see it building up to see what temperature is right." (Group 1)*

> *"I like how like you could like enter the amount of water or what temperature you wanted, and it would - you could see the plant change." (Group 3)*

Having a closer inspection of the fruits and flowers with the rotate and zoom features created opportunities for individual learning at post simulation, even in a group setting. Multiple representation of the plant growth simulation data through a visual plant model and textual information encouraged students to investigate more about the impact of temperature or water on their assigned plants by creating more simulation trials. While some students preferred consulting the plant model visuals and others preferred consulting the text outputs, most students found the combination of both was the most helpful. They reasoned that it was because the visual information of the plant model and the textual outputs coincided well with one another.

> *"Because, like, the plant growing kind of went with the information. It went with the information. It kind of coincided." (Group 2)*

While mirrored plant growth simulation within group members generated excitement, some students expressed that when multiple students from the same group tried to operate the temperature/water input slider simultaneously to input a value, that froze the system entirely. One student commented that their screen sometimes looked like there were multiple simulations running at the same time, causing some of the sliders to glitch out, which brought constant frustrations to them.

> *"And the other thing is that sometimes it looks like there are multiple simulations running at the same time. And then it would just cause like the bar to just like glitch out." (Group 1)*

Due to some technical glitches on the first day of the plant simulation experiment, some students found the grouping and ungrouping feature to be difficult to use (e.g., seeing multiple names of the same person in the friends list). Once the bug was fixed, grouping went relatively smoothly on the remaining days.

Trials Tab. We received mixed responses about the trials tab. A few students were fascinated by the seamless information flow between the simulation tab and the trials tab, but some students did not use the trials tab at all. One of them mentioned that they relied on their memory to conduct further trials, instead of going to the trials tab.

> *"My favorite part was how the data would just automatically go to the table, and you just have to write it down." (Group 3)*

> *"Honestly, no. It didn't help me very much." (Group 1)*

A few students mentioned that they tried to use the trials tab but did not like to move back and forth between the simulation and trials tabs. On the other hand, some students reported that they liked and used the trials tab constantly. They thought it was important for tracking their data over time. It was also helpful towards not forgetting which input values were tested in prior trials. Despite finding the trials tab helpful, one student felt the trial data should have been organized by the temperature/water input values instead of the trial numbers. They found it was difficult to scroll through many rows of trial information for deciding their next input value to be tested. One student commented that it was difficult to keep track of which trials were created individually and which were created in groups as all trials were displayed on the same tab.

5.2.2 Learning Experience. Some students expressed that running the plant growth simulation trials collaboratively was a fun way to learn about environmental factors and plants. While it was not a physical plant growth experiment, it still felt like one, commented by another student. One student shared that seeing the differences between the optimal ranges of temperature and water for the tomato and bell pepper plants made them realize that tomato plants need higher temperature and higher levels of water than the bell pepper plants that they consider as a learning opportunity about the environmental factors on different plants.

> *"I kind of did like compare and contrast of like the differences between the tomato and the bell pepper, and I realized like the tomato needed a little more temperature and water than the bell pepper did." (Group 3)*

5.3 Group Videos and Screen Recordings

To understand how the mirrored plant simulation supported collaboration and engagement among the group members (RQ2), we categorized the group video and screen recording data according to the framework that we presented in Table 1. We present our findings in the following subsections.

5.3.1 Mechanisms of Collaborative Discussions and Actions (Making/Accepting Suggestions and Negotiation). Overall, we observed notable collaborative discussions and actions between group members in every group. We observed that students were very excited to see the simultaneous plant growth simulation – that was supported by the mirrored plant simulation feature – with their group members, which stimulated meaningful group conversation. In general, students worked together with group members to develop strategies for finding the maximum, minimum, and ideal range of temperature and water for their assigned plants by running multiple trials of plant simulations. A common strategy that all groups used was to start with a lower value and gradually increase the temperature or water level in each trial to find the minimum, maximum, and ideal range for their assigned plants. Students negotiated the next input values for temperature or water level with their group by discussing the results from their previous trials before agreeing on the next input value. Students in most groups expressed excitement and showed enthusiasm about visualizing different stages of the plant growth, particularly when simulation resulted in healthy plants. They frequently examined and commented on the appearance of the plant after running a simulation and made remarks on the health and realism of the plant models before deciding on their next input values. The temperature/water input slider feature encouraged group conversation around the plant growth in extreme temperature and water levels as well as the temperature and water range differences observed in the different types of plants. Students also helped each other to clarify tasks and solved smaller technical challenges. For group C1G1J, the collaborative enthusiasm persisted even after the activity was over, as students 113 and 109 returned to test and view additional plant simulations, beyond their assigned plants.

5.3.2 Mechanisms of Coordinating Collaborative Discussions and Actions (Joint Attention and Awareness, Narration, Intrusion, Regulation of Access, Turn Taking). In some groups students coordinated their tasks by dividing the tasks and collaboratively monitoring their progress. Students also worked individually when simultaneous interaction caused the system to freeze. To monitor and support each other's work, some groups nominated designated members to interact with the system (*interactor*), while others narrated (*narrator*) their thought process and actions. Group C1G1J interchanged the roles of the *narrator* and *interactor* in different trials. For C2G2 group, we observed intrusion as Student 225 physically changed Student 228's input parameters, instead of verbally informing them about the wrong plant input. Our plant simulation application provided a mirrored plant simulation view for each group member, thus, no conflict on regulation of access and no turn taking was observed.

5.3.3 Additional Codes. ***Non-collaborative Interactions.*** Despite observing overall positive collaboration and coordination among group members, we sometimes noticed reduced collaborative interaction. For example, on Day 3, each group was broken up into pairs to run experiments with either temperature or water for tomato plants. For the groups with three members (e.g., C1G1, C2G1J) or with an absentee member (e.g., Student 126 of C1G2 on day 3), one member ended up working alone. While most such stand-alone members joined the conversation later with other group members, student 126 from C1G2 did not interact at all with others. For C2G2, we occasionally observed that when students coordinated and divided their work, there were episodes when they did not communicate at all and were not aware of each other's interactions and simulation results. It is possible that the lack of having defined roles as narrators and interactors resulted in these non-collaborative episodes.

Task Work. We observed that relatively more active group members sometimes took the lead in controlling the simulation and did not collaborate with others (e.g., Students 214 and 227 in C2G2J).

Off-task Interactions. Similar to a prior in-the-wild study [14], we observed some students often engaged in off-task activities, such as playing games, looking for answers on the internet, chatting about non-task related subjects, leaving the task, and falling asleep. Going off-task on the Chromebooks was common when a student either worked alone or had no interests in communicating with their group members. When task work was observed in a group, the relatively inactive members were more likely to engage in irrelevant conversation with others (e.g., Students 210 and 218 in C2G2J) or fall asleep (e.g., Student 126 from C1G2). We observed that the same students had off-task interaction throughout the study, so this may not have been a direct result of the simulation application itself.

Software Conflicts. On the first day of the plant simulation experiment (Day 3), we observed some technical difficulties (e.g., problem with joining a group) with the plant growth simulation application that shifted students' focus from the task to troubleshooting. Most of the groups worked together and helped each other to solve those technical issues. For the unsolvable issues (e.g., system latency and overloading due to simultaneous interaction), students discussed their troubleshooting plans and mostly were able to work around them. However, in some cases software conflicts resulted in frustrations and brief abandonment of tasks (e.g., Day 3 activities in C1G1J group).

6 DISCUSSION

6.1 RQ1: Usability and Difficulties

Our findings from the post-study questionnaire and interview, which were designed to evaluate the usability-related issues of the plant growth simulation application, were aligned. Data analyses from both questionnaire and interview demonstrated that students expressed an overall very positive attitude toward the plant growth simulation application. Results from the questionnaire data demonstrated that students were mostly happy with the simulation application features, particularly, the mirrored plant growth simulation feature, and rated them as *Really Good* or *Fantastic*. The interview data provided us with more insight about students' interaction with these features during the plant simulation experiment, along with their reasons behind giving such positive ratings. Most of the students expressed that the mirrored simulation of the plant growth process within a group helped them to understand the required temperature or water amount for different plants. They also enjoyed the individual control to the 3D- plant view and plant growth stage view for further plant inspection such that they could bring their own insight to the group discussions. Our observations from the group videos and screen recordings also have led to similar conclusions. The combination of visual and textual plant growth output information worked as an additional feature to improve their learning about the plants. Some students also appreciated the seamless information flow between the simulation tab and the trials tab.

Students sometimes faced difficulties during the group activities when more than one group member tried to run the plant growth simulation simultaneously, which often generated frustration. In our group video and screen recording analysis, we observed that to avoid such system overload, some groups assigned designated roles as *interactor* and *narrator* for the group members. Limiting the access of the temperature/water input slider for others, when a group member starts using it could be a future design solution to avoid this issue.

Although a few students appreciated additional representation of their previous trial data in the trials tab, we have noticed relatively low engagement with the tab. The trials tab could use some design improvements. Students commented in the interview that trials sorted by the temperature or water input value could have been more useful to decide the next input value to run the simulation. Another comment was about the need of distinguishing between the trials that are created individually and that are created in a group. Future design of the trials tab can include a sorting function for every column such that students are able to sort the trial data according to the temperature or water input value, number of flowers and fruit, or any other column header. An additional column can be added to the trials tab to indicate whether the trial was created individually or in a group. Additional information about the group that created a trial can be added as we had different group formations (original and jigsaw) in our study. These additional features may encourage the students to consult the trials tab more.

6.2 RQ2: Collaboration and Engagement

Our plant growth simulation application was built on a multi-device shared interface with mirrored plant simulation features. The mirrored simulation within the group members offered similar advantages to shared single-display groupware systems, such as having an identical visual for everyone, without hindering spatial and data autonomy as it was observed in prior studies [14, 16, 41, 51]. Having the identical visuals of the plant growth stages within a group helped to stimulate meaningful conversation among the group members. Collaboration was observed not only during the task, but also during getting familiar with the simulation application and troubleshooting.

We also noticed non-collaborative and non-coordinating episodes where students either worked individually without any joint awareness or engaged in off-task activities. While CSCL technologies can elevate collaboration, students' motivation and relationship dynamics impacted the nature of collaboration and coordination, as reported in prior work [17]. Like prior studies [17, 42], we also observed that defined roles of interactors and narrators improved coordination with joint awareness. Off-task activities were mainly influenced by lack of interest in the curriculum, lack of understanding of the task description, and not getting sufficient opportunity to participate because of other more enthusiastic group members taking control of the simulation. Improving the curriculum by having clear and simple language, incorporating elements that are appealing to middle-schoolers, and adding gamification with concurrent activities for everyone may increase motivation and participation. In our study, we did not compare groups that used our mirrored real-time plant growth simulation application with groups that did not use any simulation tool for learning middle-school Biology curriculum. Running an in-the-wild future study like that may gather additional insight on improving collaboration and engagement among the group members during Biology classroom experiments.

Success of CSCL technologies also depends on the expertise of the teachers on how to orchestrate the technology in the classroom [13]. Although we did not collect teacher's interaction data with our plant simulation application, we observed that the quality of students' collaboration improved on the later days of the study duration. It is possible that as the teacher gained more experience with our system, they were more competent in orchestrating the curriculum which in turn reflected on students' collaboration. In future, designing supplementary teaching materials for the plant growth simulation application can be considered as a potential way to improve the collaborative learning experience for the students.

Moreover, interviewing the teachers in future studies may gather valuable insight on reasons behind students going for the off-task activities.

7 CONCLUSIONS

Collaborative learning is an effective approach to learning that is grounded in social constructivism, a theory emphasizing that knowledge is co-constructed among learners. Computer Supported Collaborative Learning (CSCL) technologies can facilitate and enhance collaborative learning processes, offering innovative ways for students to interact, share information, and learn together. Our plant growth simulation application generated a notable collaborative learning experience for the students by mimicking plant growth simulation in real-time in the classrooms. Even though working on personal devices can limit collaboration in CSCL, our mirrored plant growth simulation feature for the group members provided a shared view of the plant simulation process such that students could simultaneously plan and work on their common goal. Moreover, the plant growth simulation application received overall very positive acceptance from the students. Although our study identified some difficulties that were encountered by the students, our analysis guided toward some potential solutions such as limiting multiple simultaneous plant growth simulations and effective prior trial information visualization to improve the affordance of the application and the overall collaborative learning experience for the students. In addition to improving these features, introducing more appealing Biology lesson components such as gamification and designing supplementary material for teachers to better orchestrate the class can enhance the collaborative activities in the classrooms.

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