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How Diseases Spread: Embodied Learning of Emergence with Cellulo Robots

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Abstract: Embodiment has been known to have several benefits for learning. However, implementing embodied learning in a classroom with technologies such as Kinect, augmented, virtual and mixed reality and tangible objects is a challenge because of the infrastructural and logistical constraints. In this work, we present one case of an effective implementation of an embodied learning activity in a classroom. We employed hand-held robots called Cellulo to design a mixed virtual-physical activity to help high school children learn the concepts of emergent behaviour. We found that the activity was effective for learning and was perceived as engaging and useful by the teachers and students. This work contributes to the design and practice of implementing embodied learning in a classroom.

Keywords: embodied learning, Cellulo robots, emergent behaviour

1. Introduction

In recent years, there has been a shift towards an embodied perspective to cognition, which posits an integral role of the body in thought. While theories of embodied cognition are still debating the exact mechanisms by which the body participates in cognition, they all agree that cognition is based on or dependent on bodily processes outside the brain and extrabodily processes (Newen, de Bruin & Gallagher, 2018). These theories then suggest that these embodied processes be leveraged for learning (Shapiro & Stolz, 2019), perhaps in complementary ways to traditional verbal and symbolic cognitive processes (Abrahamson et al, 2020). Embodied learning has been employed for a variety of school subjects including science (Lindgren & Johnson-Glenberg, 2013), mathematics (Abrahamson & Sanchez-Garcia, 2016; Khodr et al, 2020), language (Glenberg, 2008), social studies (Xefteris & Palaigeorgiou, 2019) and programming (Merkouris et al 2017) and has been found to be effective compared to non-embodied methods.

With the growth of technology, researchers and educators have attempted to design embodied learning activities that allow students to participate in their learning by moving their bodies in novel ways (Abrahamson & Sanchez-Garcia, 2016; Lindgren & Johnson-Glenberg, 2013; Rahman et al, 2018). These designs use augmented (AR), virtual (VR) and mixed reality (MR), hand and full body movement tracking and tangible manipulations to interface body movements with real and virtual objects. The activities embed concepts within the meaningful action performed by students in the accomplishment of a task along with sensorimotor feedback, which enables learners to improve their performance of the action (Lindgren & Johnson-Glenberg, 2013). The goal is for students to develop concrete knowledge about the concept using an embodied modality, which can then be abstracted or turned into meaning (Abrahamson et al, 2020). However, these activities often require technology set-up in the classroom that may create an orchestration load for teachers (Prieto et al, 2017).

Educational robotics represents a promising solution to facilitate students' embodied learning by introducing learning activities based on tangible manipulations and movements of real objects (Merkouris et al 2017). The Cellulo robots (Ozgur et al., 2017a) currently designed and prototyped for schools by the CHILI lab represent such an innovation in educational robotics. In particular, these robots can move and be moved, provide haptic and visual feedback and localise themselves on a dotted paper, making them versatile and generic tools. Preliminary studies have shown evidence of the

positive effect of the Cellulo robots-based learning activities on student's motivation, learning and engagement (Ozgur et al, 2017b; Khodr et al, 2020; Nasir et al, 2019; Johal et al, 2019). Further, Cellulo robots do not require extensive technological set-up besides the activity map on which the robots move and a laptop or tablet already existing in the classroom ecosystem. Given their multiple interaction and feedback options along with their ease of use, Cellulo robots are an ideal technology for implementing embodied learning in the classroom. In this paper, we design and evaluate a Cellulo-based embodied learning activity for learning the emergent behaviour of virus propagation in a regular high school science classroom. Our research questions are: 1) Do students learn the concept of virus propagation using a Cellulo-based collaborative embodied learning activity? 2) What are the perceptions of students and the teacher of conducting such an activity in a regular classroom session?

2. Literature on Design Principles for Embodied Learning

There are several views regarding the mechanisms underlying and hence the design principles for embodied learning. Some research suggests that when students move in order to reach a goal, they have to coordinate and control their movement and attention, and in doing so they may discover new sensorimotor perceptual structures that instantiate the underlying concept by design. For instance, in an embodied learning activity for the concept of proportions, children are required to move their hands so a screen in front of them stays green (Abrahamson & Sanchez-Garcia, 2016) which happens only when they maintain the distance between their hands in a particular proportion. In order to accomplish this, they have to pay attention to the distance between their hands and the color of the screen, and then control the position of their hands. In so doing they learn the notion of proportion which is captured in the position of and distance between their hands.

Another mechanism underlying embodied learning is that when learners do actions in the learning environment that are congruent or relevant to the underlying concept, the meaning of the concept is grounded in their bodily processes, which may complement, supplement or provide an alternate understanding of the concept compared to the formal verbal and symbolic processes (Kontra et al, 2012). Learners develop an embodied representation of the concept, which can then be leveraged in problem solving and reasoning along with the symbolic and verbal representations (Wilson & Golonka, 2013; Schwartz et al, 2005). For instance, researchers have shown that dynamic gestures of object transformation support geometric reasoning (Narayana et al, 2016), gestures aligned to the movement of gears support the learning of concepts of simple machines (Han & Black, 2011), tangible manipulations of mathematical symbols support the learning of algebra (Ottmar and Landy, 2017) and physically swinging an object helps the learning of the concept of centripetal forces (Lindgren & Johnson-Glenberg, 2013). However, it is important for the movement to be integrated meaningfully into the task and for learners to obtain immediate feedback on their actions (ie, see the changes happening as a result of their actions) in order to develop this embodied understanding (Majumdar et al, 2014). Technology such as Kinect, AR, VR and MR, tangible simulations and active tangibles enable the performing of such actions along with obtaining rich, multimodal feedback.

Further, research suggests that one of the processes by which actions influence cognitive processing is that of simulation (Abrahamson et al, 2020). The need to perform an action activates the body's own prediction mechanism, which uses the feedforward sensorimotor system (Bubic et al, 2010). These actions then leave "traces" in the sensorimotor system (Rahman et al, 2018) and in a new situation, these action traces along with sensory inputs are leveraged to imagine or simulate alternate possibilities and solve problems or for sense-making. Thus, our representations of a concept, object or event involve this re-imagining based on sensorimotor traces created when we first perform the actions (Kontra et al, 2012; Rahman et al, 2018).

Finally research suggests that it is important for the embodied learning to be accompanied by a phase of "reconciling" (Abrahamson et al, 2020) in which students reflect on their actions and integrate their embodied ("firsthand") knowledge with formal notions of the concept which use words and symbols ("secondhand" knowledge, Schwartz, et al 2005). This is because both firsthand knowledge, which is based on direct experience, and secondhand knowledge, which is based on removed interpretations of descriptions of experience, are necessary for reasoning and problem solving (Schwartz et al 2005). Literature also suggests that physical and imagined manipulation together are more beneficial for learning. While physical manipulation helps to ground words and

symbols, the imagined manipulation serves to activate the same sensorimotor processes necessary to utilize the grounded representations in new situations (Glenberg 2008; Majumdar et al, 2014).

Together this literature suggests the following guidelines for designing effective embodied learning activities: 1) The learner must perform actions in order to develop sensorimotor representations of a concept. 2) The actions must be aligned to the underlying concept and integrated into the task. 3) The learner must obtain rich feedback from their actions. 4) The learner must do both physical and imagined actions, and reflect on both their actions to successfully integrate both firsthand and secondhand knowledge. The advantage of Cellulo robots is that their affordances can satisfy the four design principles above and can integrate seamlessly into the classroom ecosystem using an activity map and a laptop or computer (Ozgur et al, 2017). Further the same robots can be used to design multiple activities for subjects ranging from such as Mathematics (Khodr et al, 2020; Johal et al, 2019), metrology (Ozgur et al, 2017) and computational thinking (Nasir et al, 2019) by just changing the activity map and software application, thus offering a low-cost option for schools to introduce embodied learning for a variety of subjects. Finally the same technology being used for all subjects and grades of students makes it easier for teachers to adopt and use (Prieto et al 2017). Therefore, in this paper we explore the use of Cellulo robots to design an embodied learning activity for learning the concept of how viruses propagate based on the above design principles and report on a pre-experimental classroom study to evaluate its effectiveness for learning.

3. Learning Activities

In this work we choose the concept of virus propagation which is an instance of the general concept of emergent behaviour. Emergent behavior is an outcome that arises out of the spatial and temporal interactions between parts of a system and which cannot be directly predicted from the behavior of those individual parts (Hmelo-Silver et al, 2007). For example, birds flocking together or the spread of viral diseases, such as the current COVID-19 pandemic, are emergent behaviors. Indeed, complex systems are a growing domain of study and it is important to introduce students to the concepts of complex systems as early as possible (Jacobson & Wilsensky, 2006). Hence in this project we focus on the concept of virus propagation and design a learning activity consisting of a virtual part (i.e with a computer or tablet) and a physical part (i.e with the real Cellulo robots). Based on the principles discussed in Section 2, our learning design combines physical and imagined manipulation in two different, but related learning activities that model the spread of a disease. The first activity, which helps with firsthand knowledge, is an embodied activity using tangible Cellulo robots. We use Cellulo robots as distributed agents that students can physically manipulate and move. The second one, which helps with imagined manipulation and secondhand knowledge, is a simulation using a tablet with simulated versions of the Cellulo robots, accompanied by a worksheet where students are required to describe their observations from experimenting with the simulation and interpret them. The goal of the combined activity is to develop conceptual understanding of the dynamics of virus propagation.

3.1. Activity 1: Embodied Variant with tangible Cellulo robots.

The Cellulo robots are handheld haptic-enabled mobile robots, capable of holonomic motion and absolute global localization (position and orientation (x, y, theta)) within the workspace. When placed on a paper sheet augmented with a “dot pattern”, each robot can self-localize with sub-mm accuracy via an image sensor placed underneath the robot. Moreover, each robot has a top surface equipped with 6 capacitive touch sensors as well as 6 full RGB LEDs which allow for simple visual and touch interaction. Finally, the locomotion drive system was designed to be robust against intensive physical user interaction, allowing the robot to be used to render haptic feedback and to exert a force of about 1N. Details on the electronic and mechanical design are found in (Ozgur et al., 2017). Each robot connects wirelessly to the central controller, reports to it all events (e.g pose changed) and receives from it commands (e.g. change LED pattern or track a given velocity). The central controller (either a desktop computer or a consumer-grade tablet), runs a unity application which contains the logic of the activity and coordinates the control of robots through a star network composed of point-to-point Bluetooth SPP links.

The goal of this physical activity is for students to develop an embodied sense of how the

virus propagates and to give the student an intuition of the likelihood of becoming infected through contact with a virus. In this activity, each student is responsible for one Cellulo robot which they can move around the workspace (Figure 1). At the start of the game, one Cellulo robot is randomly assigned as infected (the LEDs color is red). As the students move the Cellulos, if one infected Cellulo touches another robot, this will induce a vibration and a random value between 1 and 6 will be generated (with the aid of the purple LEDs) in accordance to a "probability of propagation". Thus, when an infected Cellulo robot (red) touches a healthy Cellulo robot (green) the student gets a haptic feedback and either the Cellulo is infected (Figure 2c) if the value of dice is equal to one, or not infected (purple) for other dice values (Figure 2b). The students keep moving their Cellulos and observe how they get infected.

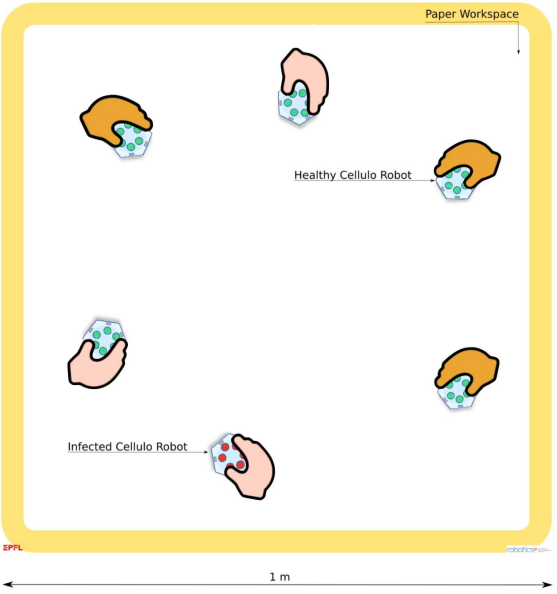
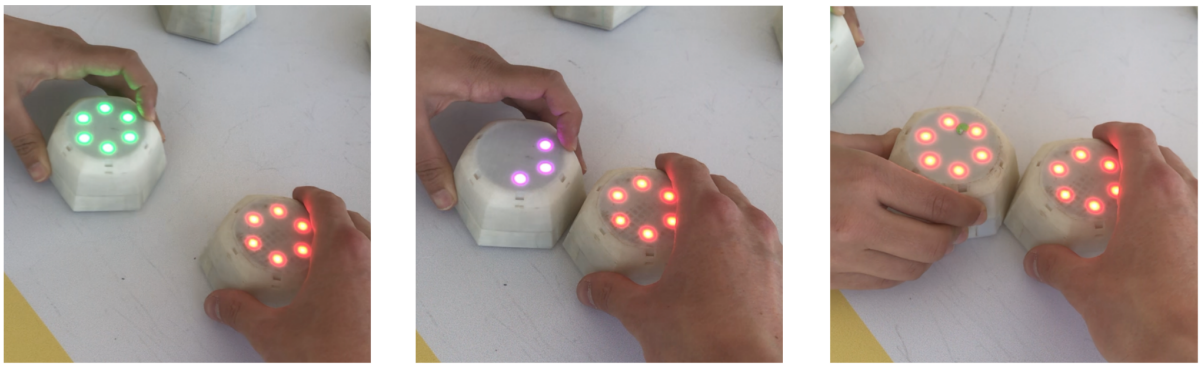


Figure 1. The set-up of the physical activity



(a) Not touched.

(b) Touched but not infected (the value of dice = 3).

(c) Touched and infected (the value of dice = 1).

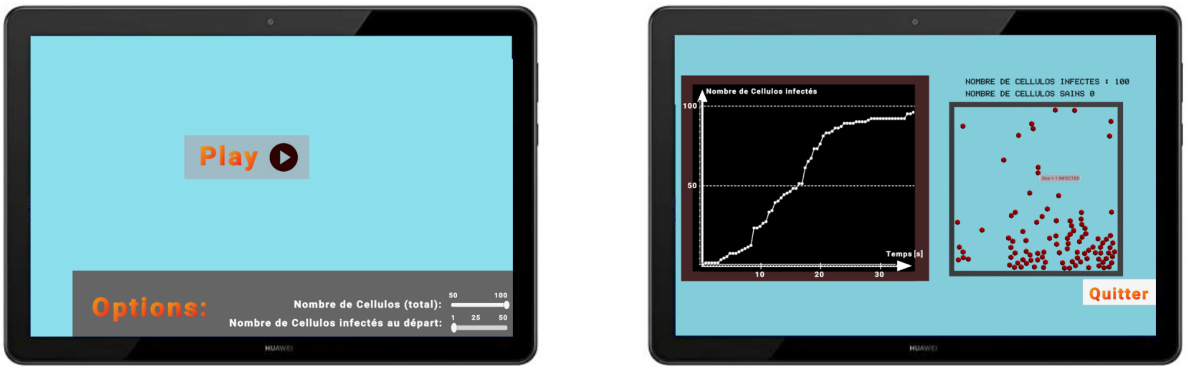
Figure 2. Examples of contact interactions between Cellulo robots

3.2. *Activity 2: Simulation Variant with virtual Cellulo robots*

The goal of this activity is to help participants understand how quickly or slowly a virus spreads in a population. Students learn how Cellulo robots propagating a disease may infect other Cellulo robots, often more than once (and then others infected would infect others) and that therefore the number of agents that are being infected each moment is itself increasing. This is depicted using two representations, the visualization of the simulated Cellulos becoming infected (Figures 4a and 4b) and the graph which shows the growth of the infected Cellulos (Figure 3b). The multiple representations help to make learners aware of exponential growth and not linear spread.

A brief overview of the activity can be seen in Figures 3 and 4. The first screen (Figure 3a) is

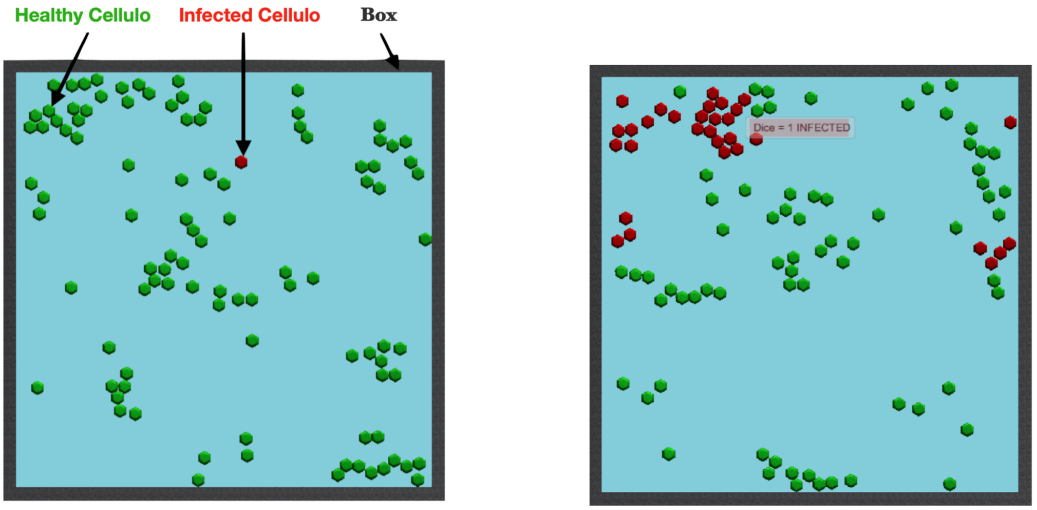
a menu page where the user can change attributes of the simulation by modifying the sliders in "Options". In this case, they can change the total number of Cellulo robots on the map or change the initial number of infected Cellulo robots. When the play button is pressed, a corresponding simulation is launched (Figure 3b) and visualized with moving virtual Cellulo robots in a containment box along with a graph showing the evolution number of infected robots at each tick of the simulation's clock. This graph serves as a basis for students to discuss modeling the spread of the disease among the Cellulos and to construct models in general. They should observe an "S-curve" as the graph in Figure 3b depicts. The learners are provided with a worksheet with instructions to vary the parameters, make predictions of the effect of these changes on the results and verify their hypotheses after interacting with the simulation as research has shown that such prompts are necessary for students to do successful exploration. As students change the total number of Cellulo robots, they increase the number of agents per area unit, making it more difficult to avoid infection and thus more infectious interactions per time unit is seen. The graph shows this phenomenon and helps students to have a better understanding of why a faster curve is observed on the graph when increasing the number of Cellulo robots.



(a) Menu of the simulation with the setting put as default.

(b) 40-second time simulation.

Figure 3. The simulation with the virtual Cellulos



(a) Simulation for time = 0 second.

(b) Simulation for time = 10 seconds.

Figure 4. Virtual interactions between the simulated Cellulo robots as time progresses

4. Methods and Materials

4.1. Participants

The study was conducted with one class of 9th grade students (13 years old). The level of these students in this school was the highest for mathematics (as they were all in maths and physics class).

The experiment lasted 70 minutes and was run with a total of 23 students (12 male, 11 female) with no prior experience with Cellulo robots. The children were split into 6 groups of 3 or 4 students.

4.2. Protocol

We performed a single group pre-experimental study to evaluate whether the designed activity is effective for learning the concepts of virus propagation. After a brief introduction and instruction session, students took a pretest which lasted for 10 minutes. Then, they were split into groups. While two groups were doing Activity 1 (physical) in a combined bigger group, four groups were each doing Activity 2 (virtual) on separate tablets. A rotation of the groups was done so everyone could experience both activities. After that, a post-test was conducted. Finally, a debriefing and conclusion session was done and the students filled a perception questionnaire.

4.3. Data Sources and Analysis

To answer our RQ1, we collected participants' scores on the pre and post tests to measure their learning gain and to answer our RQ2, we collected responses to a questionnaire to measure their perception of their learning and engagement with the activity. Further in order to understand how learners used the Cellulo robots in the physical activity, we collected logs of the robots' movements. The pre and post tests were adapted from literature (Wilensky & Abrahamson, 2006). The pretest has three questions to evaluate students' knowledge on the topic of "propagation": 1) a matching question where the student is asked to match a text about a context to the corresponding graph. The context is that, what would happen if we double the number of students everyday, one student is added each day, one student is removed daily, or one student has a cold and the cold spreads in the class. Options are four types of curves: linear (positive slope), linear (negative slope), exponential and logistic. 2) a multiple choice question where the student is asked to choose one correct answer. The context is whether the time it takes for a rumor to spread between all students would be faster, unchanged, or slower in two conditions, namely, when the number of students doubles or if the rumor is already known by half of the class. 3) a drawing question where the student needs to draw a graph for the context of mold propagation.

The posttest is similar to the pretest with a change of values, orders, and context of the questions. At the end of the experiment, students were administered a final perception questionnaire to evaluate their perception of the activities' with Cellulo from the perspectives of interest, collaboration, confidence (for solving the exercises), engagement and future interest (for including Cellulo in future mathematics lessons, as well as lessons of other disciplines). Each of these items (except the topic "interest") corresponded to a minimum of 2 questions, to acquire a more reliable estimate of the construct from the students. Internal consistency is calculated using Cronbach's alpha. With the Cellulo log data, we draw trajectories of all the Cellulos movement on the workspace for one group of learners, in order to understand how students moved them to spread/control the disease.

5. Results

5.1. Learning Gain

We calculate the learning gain as the percentage difference between pre- and post-test scores. On the pretest, the students obtained a medium score suggesting that the test is probably well designed for the level of these students and that no ceiling effect occurs. We found an increase from 57.42 (+- 15.14) % to 84.28 (+- 12.57) % in the scores when comparing post and pre-test. Although one student had a negative learning gain of -7.1%, all the other students had a positive learning gain on average of 26.87% (+- 16.42)%. A t-test revealed that there was a significant difference between the pre and post test scores ($p = 1.57e\text{-}7 < 0.05$). This implied that students showed a significant improvement in their understanding of concepts of emergence.

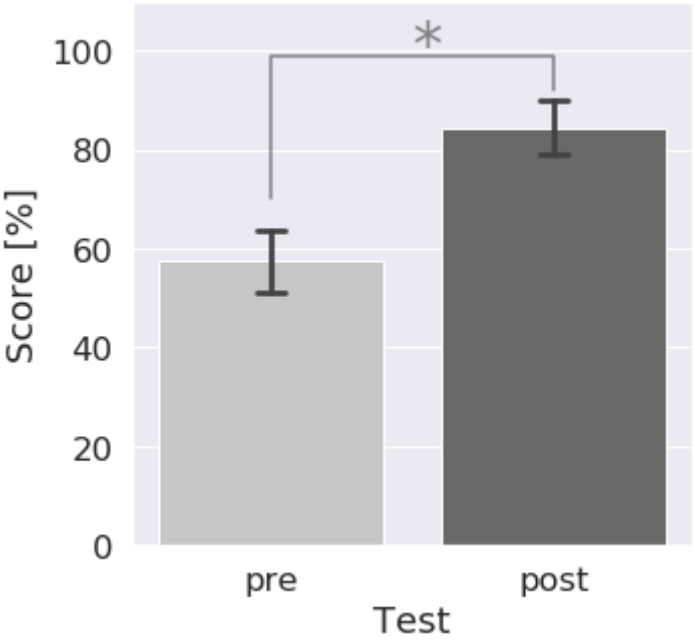


Figure 5. Learning Gain Results (* indicates a significant difference with p-value <0.05 with t-test.)

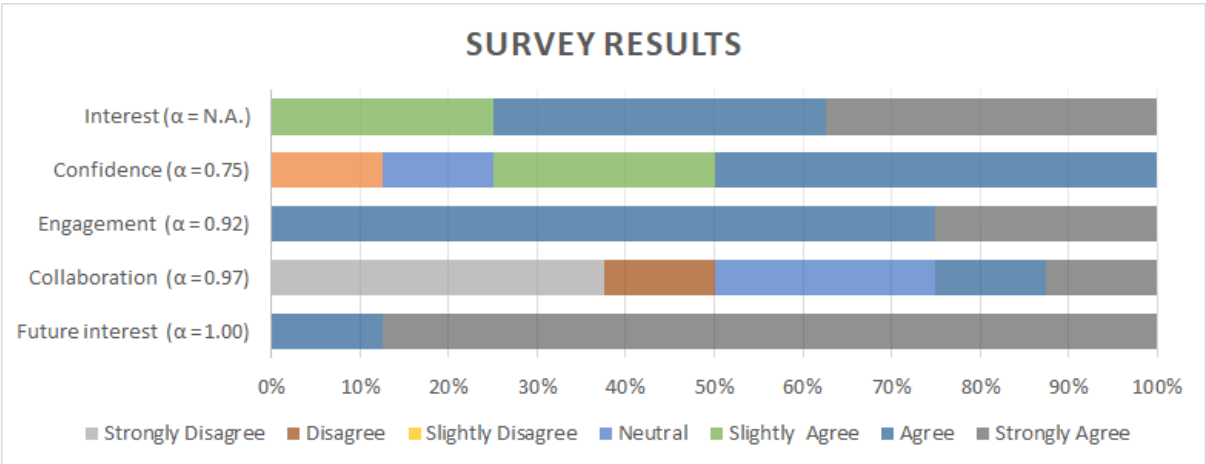


Figure 6. Student perceptions of the learning activity

5.2. *Learner Perceptions*

Figure 6 shows the results of the perception survey. Only 8 participants responded to the survey because the class had ended when the survey was given and the students were free to leave. However, the overall perception of the activity is good, especially for the future interest with 87.5 % of the students giving the maximum rating. Still, the perception of collaboration is not very positive. At first glance, this finding could be surprising because the simulation is done with a group of 4 and the activity with Cellulo robots is done with 2 groups (i.e interaction is needed). However, the school context could be the reason for this bias where all day long, students have to be silent and the discussions between classmates are not welcome during the class. This could be the reason why the students perceive collaboration negatively. Nevertheless, the results suggest that students are interested in having further Cellulo robot-based activities in this topic and for other subjects.

5.2.1. *General Feedback from teachers and students*

Informal conversations with the teacher and some of the students at the end of the experiment offered further insights into the perceptions of the participating teacher and the students. The teacher appreciated the activity as a playful and motivating way to learn about virus propagation and as they reported (translated from French) "Students were interested in class, they worked well and participated in the activities, a positive welcome. Is it possible to get the software used, or where is possible to get the activity to try to do another activity ?" Further from his point of view "It would be interesting to try with other chapters (e.g. science with biology, astronomy, etc)." However, he expressed the following challenges in conducting the activity, "A little bit too much noise during the course, the students were overexcited and they perhaps 'played' too much with the Cellulo robots (instead of learning)". Thus we infer that the teacher appreciated the learning value of the activity, but admitted that there was an orchestration challenge involved.

The students showed their enthusiasm for these activities, as seen by this sample quote from one of the students: "Incredible, fantastic come back [to the experimenter] when it's possible, I really enjoy the Cellulo." However, some students also expressed some frustrations about the experience such as 1) "It is not cool to do at the beginning of the test." 2) "Too many sheets. It is annoying to do the tests." 3) "Accuracy sometimes from the Cellulo robot is not good. And the tests are too easy." Overall, we see that the students enjoyed the experience, expressed an enthusiasm to do more such activities and their frustrations were related to the experimental protocol rather than the learning activities themselves.

5.3. Cellulo Movement

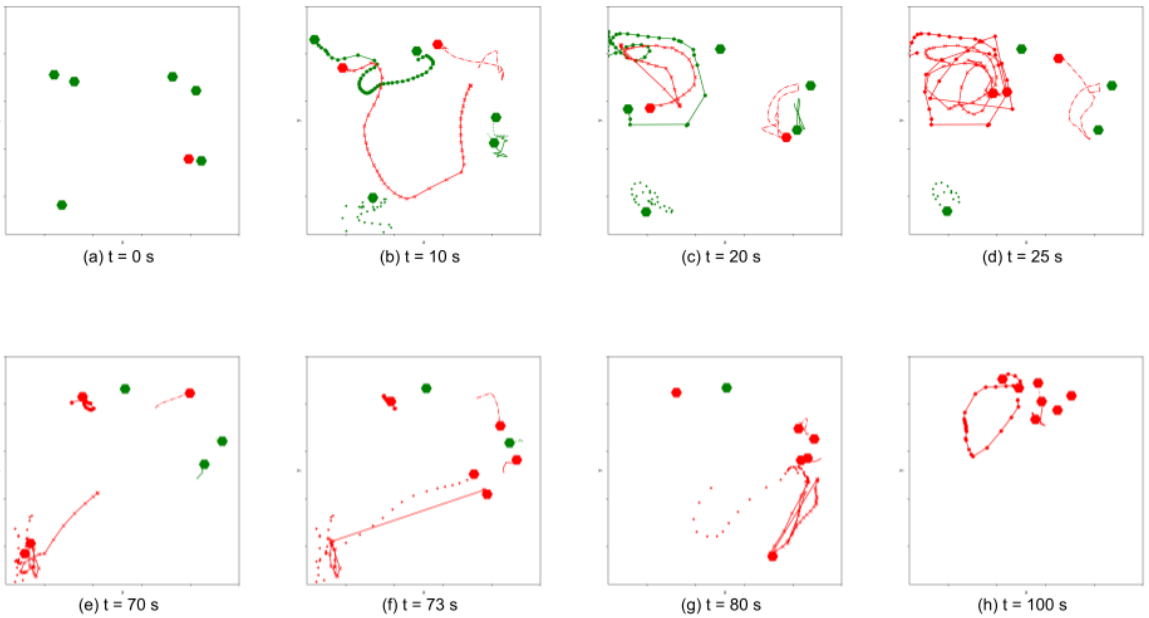


Figure 7. Cellulo trajectories during Activity 1

As the physical activity was open-ended, we explored how students used the Cellulo robots during this phase, in order to understand if the students were using it in the designed manner or not. This is important to leverage the benefits of embodiment. So we analysed the trajectory of the positions of all the Cellulo robots on the workspace over the duration of the physical activity performed by one combined group. The trajectories are shown in Figure 7, where the positions and state (infected or not) of the Cellulo robots are plotted for various times during the activity. A green hexagon marks a healthy robot, a red one an infected one. The trail indicates the trajectory taken by the robot in the last 10 seconds. We can visually infer a pattern of infected robots "chasing" the healthy ones, while the latter try to escape. "Jumps" in the lines indicate instances where students kidnap their robot (picked them up from the workspace) under the urge to catch or escape other robots. Thus we observe that by moving the Cellulo robots, students developed certain intuitive strategies for spreading the disease

(infected robots) and for avoiding being infected (healthy robots).

6. Discussion and Conclusions

In this paper, we report the design of a two part physical-virtual embodied learning activity for the conceptual understanding of emergent behaviour. We performed a pre-experimental study to evaluate the effectiveness of our design for learning concepts of virus propagation which is an instantiation of emergent behaviour. Specifically our research questions were 1) Do students learn the concept of virus propagation using a Cellulo-based collaborative embodied learning activity? 2) What are the perceptions of students and the teacher of conducting such an activity in a regular classroom session? Statistical analysis of the students' scores on the pre and post tests showed that students had a significant improvement in their scores. This shows that the two part embodied learning activity, which combines direct experience and descriptions of experience in verbal and symbolic forms, was effective for students to improve their conceptual understanding of concepts of virus propagation (Schwartz et al, 2005). Analysis of student responses to the perception questionnaire and their informal feedback suggested that students were engaged with the activity and interested in doing other similar activities. The teacher also perceived the usefulness of the activity for learning, while also pointing out the orchestration challenge in implementing the activity in a classroom. This suggests that it is possible and useful to implement such embodied learning activities in a classroom for a range of topics and domains.

We also explored the students' trajectories of moving the robots during the physical activity in an attempt to understand how students used the Cellulo robots. From students' trajectories we inferred that they performed the activity like a game, with the person holding the infected Cellulo being like the “catcher” and the others holding the infected Cellulo trying to “escape” the catcher. The infected Cellulo moved around trying to “catch” the healthy Cellulo robots, who moved around in order to avoid being infected. Thus from moving the robots in this manner and getting haptic and visual feedback when they touch an infected Cellulo, students' representation of emergence might be grounded in these actions. This could have helped them develop an intuition of how agents get infected, and how the number of infected agents grows until all the agents are infected (Han & Black, 2011; Abrahamson et al, 2020; Glenberg, 2008). These findings offer us preliminary insights into the mechanisms of embodied learning via Cellulo robots.

This is a preliminary study and so has several limitations, which we propose to address in our future work. Firstly, the order in which the students did the physical and virtual activity was decided in order to ensure optimal usage of the limited number of robots and classroom time. Thus some groups did the physical activity first and then did the virtual activity, some groups did the physical activity in the middle of doing the virtual activity and some groups did the physical activity after the virtual activity. While some literature suggests that it is better to do physical manipulation before virtual manipulation (Glenberg, 2008), for reasons of ecological validity we couldn’t maintain this order. Hence we propose to further investigate the roles of the physical and virtual activities in experimental studies, and whether and how they can be combined effectively and efficiently in a classroom. Secondly, this was a short and single intervention of 70 minutes. The novelty effect could be a factor which biased the results in this study and so we plan to do longer studies to investigate how the learning effects change. Finally, we performed a very small analysis of the Cellulo logs to explore the mechanisms of embodied learning. In order to improve the design further, we propose to collect and more deeply analyse the data of both the physical and virtual activities, to understand the strategies and processes that underlie the efficacy of embodied learning.

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