Windfield: Learning Wind Meteorology with Handheld Haptic Robots

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ABSTRACT

This article presents a learning activity and its user study involving the *Cellulo* platform, a novel versatile robotic tool designed for education. In order to show the potential of Cellulo in the classroom as part of standard curricular activities, we designed a learning activity called *Windfield* that aims to teach the atmospheric formation mechanism of wind to early middle school children. The activity involves a didactic sequence, introducing the Cellulo robots as hot air balloons and enabling children to feel the wind force through haptic feedback. We present a user study, designed in the form of a real hour-long lesson, conducted with 24 children in 8 groups who had no prior knowledge in the subject. Collaborative metrics within groups and individual performances about the learning of key concepts were measured with only the hardware and software integrated in the platform in a completely automated manner. The results show that almost all participants showed learning of symmetric aspects of wind formation while about half showed learning of asymmetric vectorial aspects that are more complex.

Keywords

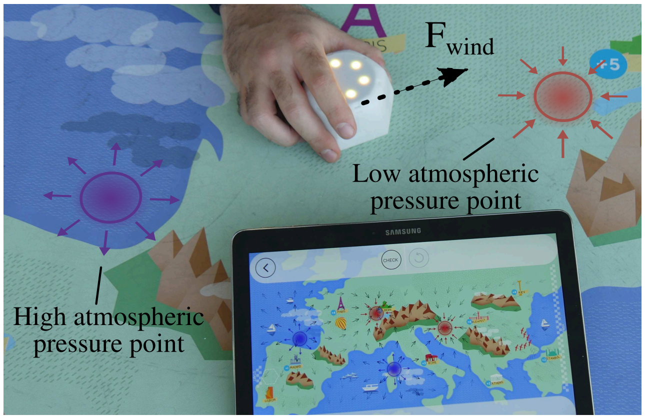
Human-Robot Interaction; Robots for Learning; Haptic Interfaces; Tangible Robots

1. INTRODUCTION

As robotics and computers became more and more present in daily activities, efforts were made in some countries during the 70's and 80's to introduce their use in school, the earliest of which was done with the Logo Turtles based on the work of Papert. Despite these institutional advances, these efforts were eventually dropped, and robots disappeared from schools for about two decades ([9]). The most prominent reason explaining this failure was that robots were expensive and unreliable, causing disinterest in educational practitioners.

One other common reason for explaining this disinterest in robotics and computer science is explained by what Gander *et al.* call the *teacher availability deadlock*: "As long as informatics is not in the curriculum, there is little incentive to educate teachers in the subject; as long as there are no teachers, there is little incentive to introduce the subject." Since Papert, many attempts were made to introduce robots in education (with subjects well beyond programming or robotics such as language) but mainly stayed limited to extra-

(a) A team of 3 learners carrying out Windfield: They are probing the map with their robots (that represent hot air balloons) to feel the winds and discover the hidden atmospheric pressure points.



(b) *Feel the Wind* interaction. Low and high pressure points are hidden in the map (overlaid in figure but not shown on paper in reality), creating winds and pushing the grasped robots. The tablet displays the map and allows the learners to guess the positions of the pressure points by drag-and-drop (all found correctly in the above instance). Directions of winds can also be displayed (seen in this instance) if the group is observed to be stuck.

Figure 1: Windfield activity and haptic interaction.

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curricular activities. The reasons for this particular limitation can be found in several studies on school teachers' opinions on robotics (such as [38, 19, 26, 17]): Besides viewing robots as expensive, resource demanding and a potential source of distraction, teachers want the technology to adapt to their practice and not the opposite. For better acceptance, such technologies should primarily target helping them achieve their duty more efficiently.

In the *Cellulo* project, our focus is to attempt to fit the current curriculum while minimizing the financial investments for schools and maximizing the usability of the robots by teachers. Our robotic platform, designed with these constraints, aims to be versatile, ubiquitous and practical. Our robots are low-cost and carry few but powerful affordances such as planar haptic and tangible interaction. They operate on printed paper sheets and are aided by consumer-grade mobile tablets; such elements are either fully (paper) or potentially (tablet) ubiquitous in the classroom. The combination of these elements results in a platform that can be easily deployed, orchestrated and maintained. The design of learning with our platform is activity-driven, where each activity is intended to teach a singular, well-defined concept found within the curriculum. A major hypothesis in our project is that many such concepts can be mapped to efficient activities with our platform so that its usage as part of daily learning life in the classroom can be justified.

In this article, we present the first complete learning activity with Cellulo, called *Windfield* (seen in Figure 1), that aims to teach the atmospheric formation mechanism of wind (introduced as part of scientific thinking and climate knowledge in schools in the country where this study was conducted) to early middle school children. Our contributions also include the design and results of an experimental user study conducted with 24 children in the form of a real hour-long lesson. Therefore, this study marks the first step towards definitively showing the educational value of the Cellulo platform. The rest of the article is as follows: After discussing the related work in Section 2, we describe in Section 3 the robotic platform used for the Windfield experiment. Then, we present the user study on Windfield in Section 4. Section 5 presents the results and discussion on our findings. Finally, we give our outlook and future plans for Cellulo in Section 6.

2. RELATED WORK

Due to the historical evolution of educational robots, teaching programming and robotics preceded all other subjects. Later, other closely-related Science, Technology, Engineering and Mathematics (STEM) subjects were brought into focus. Educational robots conceived to teach these subjects were classically designed as facilitators in learning the subject through their related inherent qualities such as programmability and sensor/actuator hardware; in other words, they played the *tool* role identified by [26]. [38] calls this approach "robots for education", and points out that the method can potentially be used to teach subjects of any kind, while also acknowledging its clear historical focus on STEM.

[5, 16] provide reviews of studies that target such topics and the devices used for this purpose; individual programmable mobile robots (often with a differential drive for locomotion) and programmable robotic construction kits seem to be the two major choices for the tool approach. Within this approach, subjects of focus include engineering ([34, 25]), mathematics and problem solving ([37, 12]), robotics and programming ([36, 2, 40, 28, 33]), physics ([43]) and STEM in general ([4]). Our work aims to venture beyond this mostly classical approach to the tool role where the robot's inherent qualities are directly mapped to the learning scenario (*e.g.* program the existing hardware or build necessary hardware from existing components to solve a task) towards an approach where the robot's *apparent* qualities are mapped to the learning scenario, *e.g.* mapping the interaction paradigms that the robot offers to a key quantity whose behavior must be understood within a curriculum topic. We hypothesize that this approach will offer more versatility and subject coverage than what is currently found in the literature.

Later on, social robots that play the role of *tutors* that provide help to learners or *peers* that stimulate learning (identified again by [26]) were introduced. These robots are often designed to exploit social aspects of interaction, and are unsurprisingly often found in the form of humanoids (such as Nao). Although these robots are applied to the teaching of a larger variety of subjects, our approach differs from these in the sense that our robots do not possess inherent or apparent intelligence or social qualities; their behaviors are designed to be practical and only seek to spark social interaction in the form of collaboration among the learners. Therefore, this class of studies is not considered here.

From another perspective, robots that enable collaborative learning may have greater potential of adoption into the classroom. Studies that are concerned with collaborative learning aim to measure social interactions among the learners and group dynamics. Such studies are relatively new and less numerous in the domain of robots for education; examples are [24] (teaching geometry) and [7, 20, 44, 15] (teaching programming and robotics). We aim to not only improve the currently lacking subject coverage, but also equip our platform with natural collaborative aspects by designing low cost, replaceable robots that operate in large numbers. If desired, multiple learners can interact simultaneously with a collaborative activity via multiple shared robots or one/multiple personally assigned robot(s). The embedded hardware on each robot can then be used to calculate several complex metrics related to collaboration, as described in Section 4.4.

Haptics is conceptually designated to be one of the main modalities of interaction within our robot-enabled learning activities, including the one discussed in this paper that utilizes a fairly large collaborative workspace that presents a significant challenge for haptics. This challenge was partly addressed by Mobile Haptic Interfaces (such as [27, 3, 11, 30] that are human-sized platforms and [1, 35] that are relatively smaller desktop robots) that were not used in educational or collaborative computer-human interaction studies so far.

Although studies that are concerned with the use of haptics in learning are limited to traditional grounded mechanisms (often off-the-shelf devices), they still present significant motivations for us to pursue haptics as a main interaction modality with our mobile robots: [22] gives a review that exposes the potential of haptics in improving motivation and attention, in kinesthetic and embodied learning, and in the learning of invisible phenomena. Moreover, a number of successful studies that focus on teaching diverse subjects across various levels of education can be found, such as biology ([23, 14, 6]), physics ([42, 10, 18, 21]), geometry ([41]) and handwriting ([8]). Nearly half of these studies show improvement in learning with the addition of haptic feedback, reinforcing our motivation to integrate meaningful haptics in our activities.

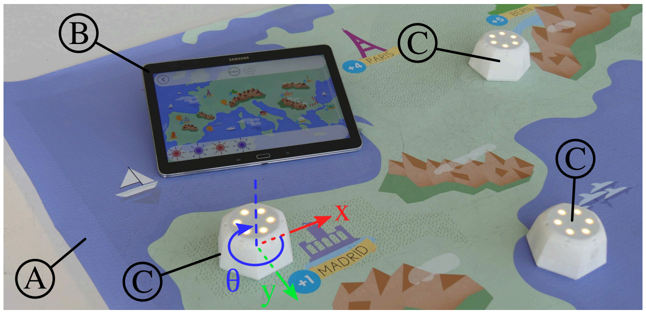

Figure 2: Typical scene from a Cellulo activity, illustrating the three main components of the platform. Ⓐ marks the paper playground containing printed graphics and the optical microdot pattern allowing the robots to localize globally with high accuracy and framerate. Ⓑ marks the tablet running the activity application software and coordinating the robots connected to it via Bluetooth. Ⓒ mark the mobile robots, each able to self-localize on the paper (with instant recovery from kidnapping), move omnidirectionally along their three DOFs (shown on one robot with (x, y, θ)) and give independent haptic feedback along the same DOFs when grasped.

3. PLATFORM DESIGN

The design of our platform was done to be practical and compatible with conditions typically found in classrooms. It is composed of three components as seen in Figure 2: Printed paper sheets that can be of quasi unlimited size, a tablet and haptic-enabled handheld mobile robots. Our robots have a plain appearance and are capable of holonomic motion, haptic feedback and absolute 3DOF global localization while on the printed paper sheets. 6 capacitive touch buttons individually illuminated with full RGB colors on the top surface provides simple in-situ input/output.

The locomotion system was designed to withstand intensive use expected in a classroom; as such, it contains measures to increase the lifetime of the components and is passively backdrivable to a degree (see [29] for details). Similar practicality concerns guided the design of the localization system, allowing each robot to self-localize with sub-mm accuracy at about 93Hz framerate while on the printed microdot pattern via a downward-facing camera found underneath the robots (see [13] for details). This design further allows the robots to recover instantly from kidnapping when returned to paper, and thus be used as active tangible items.

Each robot is connected to the consumer-grade tablet through Bluetooth 2.1 serial ports and acts as a peripheral, reporting all events (*e.g.* pose changed) and receiving commands (*e.g.* track pose goal) to/from the tablet. A cross-platform *QtQuick* application runs on the tablet to coordinate the robots and provide a graphical user interface. Latency-critical or high-bandwidth software components are built within the robots' firmware (*e.g.* motion controller, localization) while components that require high computational/memory resources or need to change depending on the activity are offloaded to the per-activity QtQuick applications that run on the tablet.

Considering these resource requirements, a classroom is required to obtain the necessary number of robots (that cost about €125 each at the prototype stage), acquire the necessary number of mobile tablets (that are becoming more and more affordable and are likely already available within the school) and have the poster-sized activity sheets produced in common printing houses. At this point, launching the desired educational activity on demand is as effortless as running the mobile application on the tablets, unrolling the activity sheets and associating the necessary number of robots (that are identical and exchangeable) with the application by releasing them on the activity sheets.

4. WINDFIELD EXPERIMENT

4.1 Activity Design

Windfield is designed as a semi-gamified activity where learners are taught how atmospheric pressure results in winds through a robotic simulation of "hot air balloons" over Europe. Wind meteorology was carefully selected from an early middle-school curriculum as a subject that is not particularly taught in detail, as a means to better demonstrate the additional value that Cellulo brings.

An overview of the activity can be seen in Figure 1. There are high and low pressure points of various intensities that create outwards and inwards winds respectively at a distance; the strength of these wind forces are decayed with squared distance. The wind force at any given point on the map is then calculated as the vectorial sum of the wind forces created by all pressure points. Other factors that affect realistic winds such as the Coriolis effect are not considered for simplicity of the taught concept. There are two distinct phases to the activity that both take place on the same 0.76m × 1.7m activity sheet partially seen in Figure 1a, hereafter called the *playground*.

Feel the Wind is the first phase where pressure points are hidden and the robots (*i.e.* hot air balloons) are used as tangible haptic devices (interaction scheme seen in Figure 1b) to probe desired points on the playground to feel the wind and discover the hidden pressure points. Learners are allocated one robot each and place their guesses as a team on the tablet's graphical display where the entire playground and each robot's hot air balloon are displayed in real time. The robots (*i.e.* tangibles) are intended to be visually mapped by the learners onto their hot air balloon counterparts on the tablet display via graphical landmarks found on the playground (*e.g.* cities, mountain ranges, clouds, boats, flock of birds, dolphins). This allows reasoning as to whether the particular forces applied to the robots are meaningful upon placing pressure point guesses on the display, since they are visible on the tablet but not on the paper playground.

Each robot in the activity self-localizes as soon as it is placed on the playground and sends its global position to the tablet application. Upon receiving a position, the tablet application calculates the virtual wind force at that position (depending on the configuration of pressure points) and sends back the locomotion output command to the robot (scaled to fit the robot's output limits). This output is effectuated as long as the learner's grasp is detected via the touch keys on top of the robot, resulting in force feedback that represents the wind force. Furthermore, in order to reduce the natural frictional impedance of the robot (due to partial passive backdrivability of the wheels) during external manipulation, a portion of the velocity vector (estimated by localization

	Phase	Goals	Time (min)
IN.	Introduction	Introduction to platform and lesson Assessment of pre-knowledge by discussion on weather forecast video	5
F2.	*Feel the Wind* with 2 pressure points	Exploration of wind and pressure mechanism with robots	10
IV.	Informative video	Comprehension of wind mechanism and mid-term synthesis	5
F4.	*Feel the Wind* with 4 pressure points	Application of wind mechanism knowledge	15
CW.	*Control the Wind*	Transfer of knowledge into constructive use	10-20
PT.	Closing & post-test	Measurement of knowledge gain	5
			Total: 50-60

Table 1: Didactic sequence in the Windfield lesson.

(a) Low pressure point (b) High pressure point

Figure 3: Pressure point icons used in *Feel the Wind*.

poses) is internally summed to the locomotion output. This enhances the comfort while the robot is being dragged across the playground, and is therefore called *backdrive assist*.

Control the Wind is the second phase where positions and strengths of the pressure points are under the control of learners to create the necessary winds to bring one robot (*i.e.* hot air balloon) from the start position to the finish line, stopping by as many cities as possible to collect the most points without leaving the playground. Learners place the pressure points, designate their intensities and start the simulation through the tablet. One robot (now functioning as a mobile robot and not a haptic device) enacts the simulation with a simple pose tracking motion controller whose target is commanded by the tablet application upon receiving the poses periodically sent by the robot.

This activity is a second revision over our previous work where only *Feel the Wind* was present with a simple velocity controller that provided the haptic feedback and grasp detection that relied on high-level key presses. This first revision was improved with a more advanced haptics controller, better grasp detection and backdrive assist as described above. For performance reasons, the simplified Finite Element Analysis method previously used for simulating the wind forces was replaced with analytic calculation. *Control the Wind* was added to give the didactic flow to the activity that lets the learners discover the effects of atmospheric pressure points at their discretion and then lets them transfer this knowledge and use it constructively in a game.

4.2 Lesson Design

A lesson taking between 50 and 60 minutes was designed with the above activity components; its didactic sequence can be seen in Table 1. During the lesson, the experimenters act only as observers and facilitators; the learners are left to interact with the system by themselves during each phase involving the Cellulo platform, with the tablet providing enough information for them to be autonomous. All phases in the lesson are explained below.

Figure 4: Screenshot from F2 (*Feel the Wind* with 2 pressure points). Visuals in F4 look similar. The low pressure point is found; the high pressure point is yet to be discovered. Vector field representation of wind intensities and directions are not normally shown to the group unless they are observed to be stuck or are nearing the time limit.

4.2.1 *Introduction* (IN)

The group of 3 learners are first greeted and shown a 1 minute video clip of a TV news weather broadcast where the meteorology reporter gives the current atmospheric pressure status. They are asked whether they are already familiar with the concepts used in the broadcast to verify the absence of pre-knowledge on the subject. They are then explained the subject of the lesson they are about to experience and how it is connected to this everyday occurrence whose underlying principle possibly evades their attention. They are explained that the high and low pressure points blow air outwards and absorb air inwards respectively and that they have effects at a distance that diminish when moved away. These facts are explained in the presence of brief slides that show the same icons used in the activity for high and low pressure points for easier retention; these are shown in Figure 3.

4.2.2 *Feel the Wind with 2 pressure points* (F2)

The learners are then invited over to the activity sheet and are given one robot each. They are told to put the robots on the map to feel the wind at desired locations; they are made aware of the depictions of hot air balloons that are continuously displayed on the tablet screen. They are also shown how to drag and drop the pressure points on the tablet to make guesses. At this point, the experimenters completely stop interacting with the group and let them do the activity on their own until the time limit. A sample screenshot displaying this task is seen in Figure 4.

One high pressure and one low pressure point (same intensity and opposite directionality) are hidden at random positions that are at least 200mm apart from each other. They are not given more information unless they are observed to be stuck or are nearing the 10 minutes limit. At this point, they are shown the wind directions and strengths on the entire map in the form of a vector field display on the tablet. If the pressure points are found with the help of this display, the learners are invited to nevertheless feel around the pressure point with their robots.

4.2.3 *Informative video (***IV***)*

After the brief introduction to the activity, the learners are shown a 5 minutes informative video from a TV show called *C'est pas Sorcier*[1] aimed at explaining scientific phenomena to young children. The short clip explains how hot and cold air loses and gains density and therefore pressure with respect to its surroundings. It continues to explain how masses of air displace between these areas, resulting in winds. In the video, the same colors are used to depict high/low pressure points as in our activity.

4.2.4 *Feel the Wind with 4 pressure points (***F4***)*

After **IV**, the learners are invited to discover 2 high and 2 low pressure points (all having the same intensity) positioned randomly that are again at least 200mm apart from each other. If they are observed to be stuck nearing the 15 minute limit, they are again shown the wind vector field all over the playground on the tablet.

4.2.5 *Control the Wind (***CW***)*

The learners are explained that in this next task, they are supposed to position 3 low and 3 high pressure points themselves in order to move one balloon across the playground and collect points by visiting cities. Points associated with cities were chosen according to how difficult they are to visit, and the cities were distributed such that it is practically possible to visit only a subset of them. They are shown how to modify the intensity of the pressure points and how to start and reset the simulation and are not aided further.

They are not given the ability to modify the directionality of the pressure points in order to encourage them to use both high and low pressure dynamics in different situations. They do this task as a team as there is a single simulation to be optimized. The progress of the group is monitored and the task is allowed to continue up to 20 minutes if room for more progress is clearly observed. Otherwise, it is finished at the 10 minute limit.

4.2.6 *Closing & Post-test (***PT***)*

Finally, each individual member of the group is subjected to a post test composed of 4 questions (with increasing difficulty) that assess different aspects of the wind formation mechanism that should have been understood in result of the lesson. Each question displays a number of pressure points on the playground and asks the learner to draw an arrow depicting the blow of the wind in that hypothetical scenario. Screenshots depicting each question is given in Figure 5; they are the following, with the aspect that must be understood to answer correctly given in quotes:

Q1. Two p.p. – *"Wind blows from high to low pressure"*
Q2. Three p.p. – *"Identical pressures have similar effect at similar distance"*
Q3. Two p.p., wind in a specific area is asked – *"At similar distance, opposite pressures' vectoral effects combine to result in winds parallel to the line that connects them"*
Q4. Three p.p., wind in a specific area is asked – *"At dissimilar distances, pressure that is closer has a larger vectoral effect; the resulting wind is the sum of these vectors"*

Learners are prevented from sharing information during the post-test. After the post-test, the learners are asked their general opinions about the lesson and are thanked for their participation.

4.3 Participants & Data Collection

24 learners (12M, 12F, 11.9 ± 0.900 years-old, min. 10, max. 13) participated in the experiment in 8 groups of 3 learners during 2 days. It was verified through the age group selection (*i.e.* younger than when this subject is taught at school) and through the brief discussion in the **IN** phase that no formal pre-knowledge existed about the subject. The groups were formed randomly and treated separately. Each group was observed for behaviors that may explain findings later on. Poses of all robots used by all learners in all groups were recorded with maximum framerate (about 93Hz) as long as on the playground. In addition, all grasp and release events, all kidnap and return to playground events and all GUI events (such as button click, drag and drop positions *etc.*) were recorded.

4.4 Calculated Metrics

In addition to task completion times, **CW** scores and accuracy of given answers to correct answers in **PT**, a number of other more complex metrics were calculated from the robot position sequences obtained from **F4**. These are given below.

4.4.1 *Similarity of exploration across entire* **F4**

We build the (per learner) 2D histogram of all visited positions where each bin is 20mm×20mm and contains the total time spent by the robot at that location. Then, we calculate the *soft cosine similarity* ([39]) across all pairs of learners within groups, defined as:

$$S(t^a, t^b) = \frac{\sum_i^N \sum_j^N s_{ij} t_i^a t_j^b}{\sqrt{\sum_i^N \sum_j^N s_{ij} t_i^a t_j^a}\sqrt{\sum_i^N \sum_j^N s_{ij} t_i^b t_j^b}} \qquad (1)$$

where N is the number of bins, t_i^l is the time spent at bin i by learner l and s_{ij} is the similarity index between bin i and bin j, which is calculated as:

$$s_{ij} = \begin{cases} \frac{D-d_{ij}}{D}, & \text{if } d_{ij} < D \\ 0, & \text{otherwise} \end{cases} \qquad (2)$$

where d_{ij} is the physical distance between the centers of bins i and j. D is the maximum distance to be considered for

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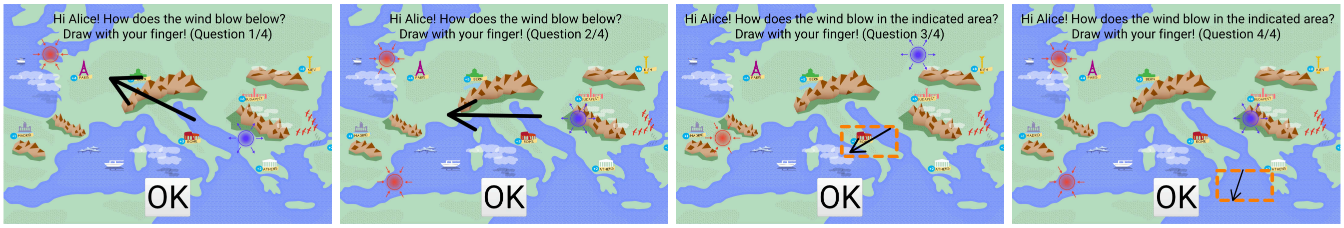
[1] English: *It's not Magic*, can be viewed at `www.youtube.com/watch?v=mmenMWUKtOO` with subtitles



(a) **Q1:** 2 p.p. (b) **Q2:** 3 p.p. (c) **Q3:** 2 p.p.; draw in the box (d) **Q4:** 3 p.p.; draw in the box

Figure 5: Post-test questions. Roughly correct answers drawn on each question.

similarity, which is chosen as the maximum size of one robot (corner to corner, 85mm).

The similarity measure indicates the likeness of spatial coverage between two learners, and may provide insights on collaboration quality within a group. High similarity may indicate redundancy of exploration (implying low collaboration quality), but may also indicate co-exploration (and not necessarily low quality collaboration) if leader-follower effects are present. On the other hand, low similarity may indicate efficient exploration by division of labor, indicating high collaboration quality, if enough communication is present within the group.

4.4.2 *Entropy of exploration across entire* F4

With the same histograms as above, as well as with the overall histograms per group, we calculate the normalized Shannon entropy as follows:

$$H(t) = -\frac{1}{\log_2 N} \sum\nolimits_i^N \hat{t_i} \log_2 \hat{t_i} \qquad (3)$$

where N is the number of bins and $\hat{t_i}$ is the time spent at bin i, normalized by the total time spent over all bins. Entropy measures the "disorder" of exploration; higher entropy corresponds to more equal distribution of time spent across the explored area (and *not* the entire playground area), while low entropy corresponds to less equal time distribution, possibly due to time spent around focal points. Therefore, lower entropy may indicate "getting stuck at" or returning to certain points rather than exploring the map without revisiting previous locations.

4.4.3 *Cross recurrence of exploration in* F4

To extract temporal information, robot positions of each learner were resampled at 1Hz (averaging all available positions closest in time) starting at the same instance to obtain synchronized positions within groups, since current robot hardware does not offer this synchronization mechanism across multiple robots. With these synchronized positions, cross recurrences between all pairs in each group were calculated (inspired by [32] in the eye tracking literature):

$$R^{ab}(t_i,t_j) = \begin{cases} 1, & \text{if } d^{ab}(t_i,t_j) < D_{\min} \\ \frac{D_{\max}-d^{ab}(t_i,t_j)}{D_{\max}-D_{\min}}, & \text{if } D_{\min} \le d^{ab}(t_i,t_j) \le D_{\max} \\ 0, & \text{otherwise} \end{cases} \qquad (4)$$

where $d^{ab}(t_i,t_j)$ is the distance between learner a's robot position at time t_i and learner b's robot position at time t_j, $D_{\min}$ is the distance below which there is full recurrence (chosen as one robot width, *i.e.* 85mm, since two robots cannot occupy the same space at the same time) and $D_{\max}$ is the maximum allowed distance for recurrence (chosen as two robot widths, *i.e.* 170mm). With this, we measure the normalized leader-follower relationship index, calculated as:

$$L^{ab} = \frac{\sum_{0 \le t_j - t_i \le S} R^{ab}(t_i,t_j)}{\sum_{0 \le t_j - t_i \le S} A^a(t_i) A^b(t_j)} \qquad (5)$$

where S is the maximum time difference to consider (chosen as 10 seconds) and $A^l(t)$ equals 1 if learner l's robot is on the playground and is being grasped at time t (*i.e.* active), and equals 0 otherwise. By definition, L^{ab} is between 0 (no leadership) and 1 (a leads b 100% of the time).

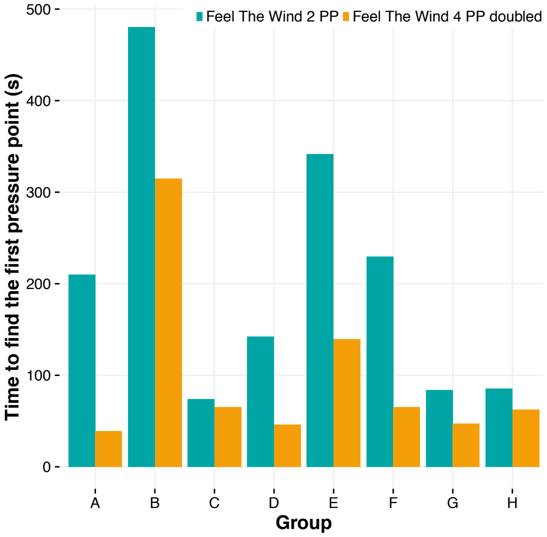
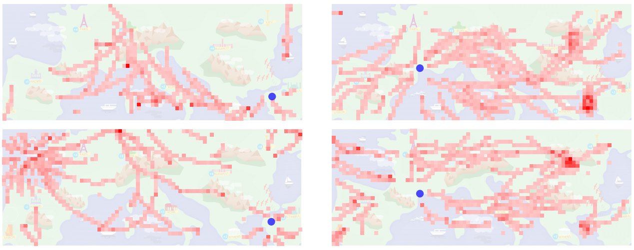


Figure 6: Time to find the first pressure point for each group in F2 (Feel the Wind 2 PP) and F4 (Feel the Wind 4 PP). F4 times are artificially doubled to acommodate twice the point density in F4.

5. RESULTS & DISCUSSION

5.1 Feel the Wind

We measured the time to find the first pressure point in **F2** and **F4** (time for each group presented in Figure 6) to determine the effect of midterm synthesis with the informative video. Comparison was done after doubling the time in **F4** due to double the density of points on the playground. A paired t-test (within group) showed significant decrease



(a) Two learners in group B. Top and bottom learners approach the same point from 3 and 6 different angles respectively.

(b) Two learners in group F. Top and bottom learners approach the same point from 6 and 4 different angles respectively.

Figure 7: Similar "approach" patterns towards high pressure points (marked with blue dots) found in two different groups. Low pressure points also clearly visible in group F as the two high density areas towards the east. Some focal points and traversals are visible over Mediterranean islands and boats, assumed by learners to host pressure points.

($t(7) = 3.9773, p = 0.005$) from **F2** ($M = 205, SD = 144$) to **F4** ($M = 97, SD = 93$). This improvement hints at the effect of the informative video, but it should be noted that this improvement may also be due to natural habituation to the platform, as all participants interacted with our robots for the very first time in **F2**.

During **F2** and **F4**, all groups were observed to find a low pressure point first as these points naturally act as "sinkholes" and lead the robots to themselves when they are allowed to move. While this agrees with our previous findings, we are not able to prevent this degradation of haptic interaction as it requires force sensing that is not yet implemented on our robots. However, in **F4**, some groups eventually found all pressure points while the rest found at least one high pressure point before being shown the visual vector field representation of winds, at which point they found the final point within a few seconds.

Furthermore, positional densities of individual robots over the entire playground revealed certain patterns of interaction, seen in Figure 7. In certain groups, learners developed the strategy where they "approach" suspected high pressure points from different angles. In almost all groups, focal points of high density coinciding with low pressure points are observed due to the aforementioned "sinkhole" effect. More interestingly, focal points and traversals are observed over graphical items found on the playground sheet (*e.g.* boats, islands, cities) some of which can be seen in Figure 7. While not intentional by design, this phenomenon agrees with our observations of the dialogue within most groups; learners often thought that pressure points should be located on such graphics and conveyed this towards their groupmates.

From a broader perspective, the total entropies of groups were found to be correlated with their average similarities in **F4** (Pearson's $r = 0.908, n = 6, p = 0.0018$). This implies that members of groups who were spending time more uniformly in their spatial exploration (not necessarily exploring more or less area) tended to cover similar areas. This may indicate that more uniform groups scanned similar areas without staying at focal points (which typically corresponded to low pressure points because of the aforementioned "sinkhole" effect) compared to less uniform groups who covered dissimilar areas and stayed at more focal points; this can suggest a difference in collaboration quality.

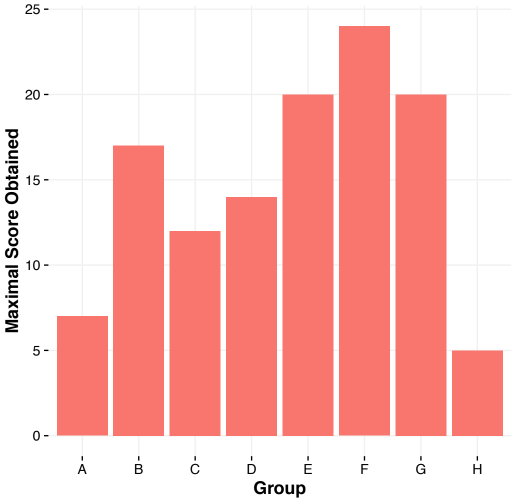


Figure 8: Maximal scores obtained by each group in CW. 31 points are available in total (intentionally made impossible to fully obtain).

5.2 Control the Wind

Figure 8 illustrates the maximal scores attained by groups during the entire **CW**. The maximal scores are observed to be widely varying across groups ($M = 14.88, SD = 6.64, \min = 5, \max = 24$), but were not found to be correlated with the number of attempts ($M = 45, SD = 36.2, \min = 17, \max = 123$). Furthermore, the scores were not found to be correlated with any metric from Feel the Wind, preventing us from drawing conclusions about the transfer of knowledge. This was likely due to the trial-and-error natured approach observed from most groups allowed by the design of the activity; this is acknowledged as a shortcoming and discussed in the following section.

5.3 Post-test

The accuracy of the answers given to the questions described in Section 4.2.6 were measured by computing the angle difference between the answer and the actual wind direction, considering answers with less than 30° difference correct. This revealed three distinct categories of answers: Correct ones, incorrect ones and ones that are exactly the opposite of correct answers. We interpreted this latter type as the learner failing to recall the correct association between push/pull and the depictions of high/low pressure points, but otherwise showing correct understanding of that particular wind formation aspect. Therefore, we labeled these answers as semi-correct (with again 30° tolerance).

Figure 9 shows the partition of each answer type for each group and each question. Scores for **Q1** (96% correct or semi-correct) and **Q2** (92% correct or semi-correct) indicate that most learners understood the directionality and symmetry of wind at central locations. Scores for **Q3** (58% correct or semi-correct) and **Q4** (42% correct) show a clear drop in performance, as these questions were more complex and required the understanding of diminishing wind intensity

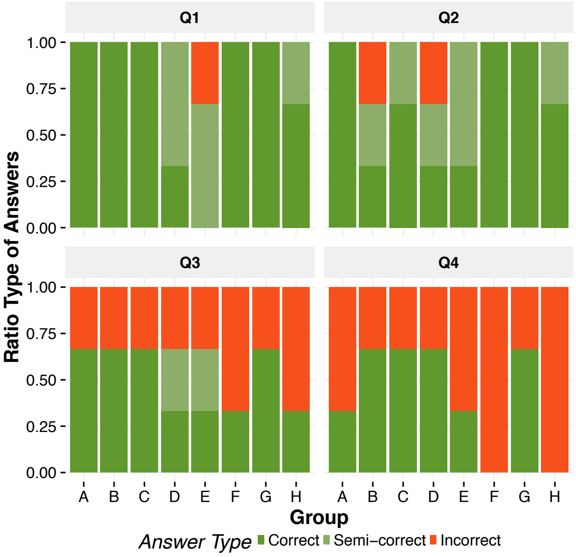


Figure 9: Ratio of type of answers for each group and post-test question. "Correct": answers with 30° accuracy. "Semi-correct": answers with 30° accuracy in the complete opposite direction. "Incorrect": any other answer.

with distance and asymmetrical vector summation. When correctness and semi-correctness of individual scores are considered among all learners, it is seen that 33% of them are 50% successful, 46% of them are 75% successful, and 21% of them are 100% successful. This implies that all learners are at least 50% correct or semi-correct.

Finally, the correlation between metrics described in the previous Section and post test scores were investigated. The absolute raw differences between correct and given angles were found to fall just short of being significantly inversely correlated with total group entropies (Pearson's $r = -0.678, n = 6, p = 0.065$); further study may indicate that learners that "do not get stuck in focal points" tend to gain more understanding of the subject phenomenon and perform better in such an activity. This is also suggested by our observations of certain groups where the "sinkhole" effect mentioned previously inadvertently pulled the robots into the (already correctly found) low pressure points and the learners visited the same location over and over again, decreasing entropy and exploration quality.

No other correlation was found between the post test scores and other measures, direct (time to find low/high pressure points, **CW** scores, number of trials in **CW**) or calculated (mean S and L within groups). This may imply that such collaboration metrics in their aggregated form may be inappropriate for predicting learning gains, or simply that there is need for more data. In any case, stronger hypotheses and data from more participants are required in the future to measure the relation between these exploration and collaboration metrics and actual learning gains.

6. CONCLUSION & FUTURE WORK

This paper introduced the first rigorously designed and studied learning activity using the Cellulo platform, the subject of which was selected from within the actual school curriculum. We presented a lesson designed with the activity and its didactic sequence to let learners explore, apply and transfer the knowledge of simple wind meteorology using handheld mobile robots. Vastly different interaction modalities that incorporate these handheld robots were used during this sequence, such as haptic and paper-based tangible interaction. These were all easily understood and effectively used: All groups found a significant portion of pressure points within time in **F2** and **F4**, most groups earned a significant portion of the total score (intentionally made impossible to fully obtain) in **CW**. Almost all learners showed learning of symmetric aspects of wind formation while about half showed learning of more complex, asymmetric vectoral aspects.

There are a number of shortcomings of the platform and the activity design. The grasp detection mechanism that uses the capacitive touch buttons does not allow closed loop control on the haptic feedback and modulating the output based on the detected grasp does not guarantee precise haptic output, allowing the learners to release the robots and follow their motion which is due to the motor outputs intended for haptic feedback. To mitigate these problems, we are investigating force/torque sensors to be installed on the outer shell of the robot; [31] is a promising candidate for this purpose. In addition, the user study was conducted with a limited number of participants, and more could allow us to obtain clearer results on learning gains.

From a didactic point of view, Feel the Wind tasks contain randomness when distributing the pressure points to cover a larger set of situations that also resulted in an undesirable chance factor in our user study. Pressure points could have been intentionally placed to induce certain situations and learners could have been encouraged to understand these specific situations. This consideration may aid in improving the learning of the subject's aforementioned asymmetric vectoral aspects by focusing on cases that involve such situations. Furthermore, Control the Wind was observed to attract trial-and-error based approaches and to be too sensitive to the position of pressure points; its design should be refined in order to negate these effects. A discretization over space for setting pressure points or a wait time (forcing predictive thinking) before the next trial may solve these issues.

During the study, a control group was not used as we do not yet claim to improve learning (compared to *e.g.* existing robotic platforms or classical teaching methods) but rather to show that Cellulo is indeed usable as a "tool" to teach an actual curricular subject. Using this study as a stepping stone, we will attempt to break the *teacher availability deadlock* by exhibiting these concrete results to educators. Therefore, in order to definitively prove the versatility and the educational potential of Cellulo, we are currently designing new activities with teachers that will soon be tested in classrooms. In the longer term, we plan to test activities with the same learner groups in the same classrooms in order to eliminate the novelty effect (that may have influenced the learners' engagement in this study) and measure the acceptance of Cellulo as a teaching tool.

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