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Abstract: Technology to support Mobile Computer Supported Collaborative Learning (MCSCL) is a compromise between screen space and mobility. While MCSCL usually leverages small portable screens, such as tablets or smartphones, large interactive tabletops have been found to effectively support collaborative learning. In this case study, we strike a compromise by using small portable screens on a large static surface by using dynamic peephole interactions. The proposed technology allows learners to augment static surfaces, such as paper maps, by sliding a tablet or a smartphone on it. A comparative exploratory study was conducted on eight groups of four K12 students. Results point to enhanced cognitive awareness among group members.

1 INTRODUCTION

Computer Supported Collaborative Learning (CSCL) has emerged in the last 30 years from the idea that computing devices can enrich the learning experience of groups of learners or professionals (Stahl *et al.*, 2006). However, the shape and size of devices used for CSCL varies. Large tabletops have been extensively used in research projects but remain niche in everyday classes, due to their high cost (currently 1200€ and above) as well as their immobility. Mobile CSCL (MCSCL), focuses on the use of more affordable and mobile devices, such as smartphones and tablets, for collaborative situated learning settings such as field trips. However, mobile devices lack the screen space that a typical CSCL device, such as a tabletop, can provide to access and manipulate virtual artefacts.

Augmented Reality (AR) can be used to transform available surfaces into interactive working areas. Yet, classic camera-based AR technology requires the device to be held at a certain distance from the augmented surface. This results in two issues: Extended use can lead to muscle fatigue (Pereira *et al.*, 2013) and holding the device with both hands can make it challenging to interact with virtual or physical objects at the same time, especially for children. Additionally, using AR in a group setting raises its own set of challenges. If a person holds a single device, others in the group have to gather around this person to view the augmented content. Alternatively, if all group members use their own device, this reduces awareness of what other group members or the teacher are doing, which is crucial for collaboration.

AR goggles, such as Microsoft's HoloLens, could address these issues but remain expensive hardware for educational contexts (4000€ per item) and introduce other problems such as motion sickness (Kaufeld *et al.*, 2022). Those devices also rely on additional controllers, voice or gestures for interaction.

In this paper, we present an exploratory study with a low-cost mobile 2D dynamic **peephole interaction**. This type of interaction enables the use of mobile devices, with smaller screens, to view and interact with augmentations on a surface. Mehra *et al.* (2006) distinguish two types of peephole interactions. ***Static peephole interactions*** require the user to drag and scroll the content on the available screen via touch gestures or a computer mouse to access content

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beyond the display's size (*e.g.* in *Google Maps*), whereas ***dynamic peephole interactions*** enable users to access content by moving and pointing the device itself to the physical position to which virtual content is associated. In the latter, the *device* effectively becomes a *mobile* window into a virtual overlay of the environment. SPART, short for on-Surface Positioning for Augmented RealiTy (see figure 1), offers a dynamic peephole interaction which allows to physically place a mobile device on a horizontal surface and navigate the virtual space by sliding it on the surface.

This is a very promising type of interaction, since it offers the same large working space as a tabletop but with affordable and mobile tablets and smartphones. Research on screen sizes also suggests that smaller screens have the potential to benefit collaboration further, as large tabletops tend to attract user's attention to the screen at the demise of social awareness of other team members - even when attention to the screen is not required. Smaller screens seem to distract users less and lead to a more goal oriented usage (Zagermann *et al.*, 2016).

Figure 1: SPART, a horizontal, dynamic peephole interaction.

Yet, little research has been conducted on this particular dynamic peephole interaction setup, primarily because it cannot be enacted using traditional AR technology.

Consequently, a device enabling such a setup was developed (Simon *et al.*, 2024). In order to compare SPART (dynamic peephole interaction) to a static peephole interaction in collaborative group work, we then conducted a study on eight groups of four K12 students during an educational activity.

This paper is focused on this exploratory study, initially introducing existing work, before detailing what aspects of collaborative learning have been examined during the study and describing in detail the activity design and the deployed research method. We then present observations and results. Finally, we discuss study limitations and conclude with future developments in terms of activity design, technology and research perspectives.

2 PREVIOUS WORK

Among the most cited papers for dynamic peephole interactions in collaboration is Sanneblad *et al.*'s work (2006) on a device to facilitate routing activities with a tablet in front of a projected, *vertical* map. The authors note that absolute positioning, as required for the peephole interaction, is not trivial to implement. In their setup, a stationary Mimio XI system (commercial ultrasound & infrared location setup for digital whiteboards, 700€) was connected to a laptop. In a preliminary user study, this setup was compared to a static peephole interaction as used in current map navigation (zoom and drag). Users' efficiency on the vertical dynamic peephole setup was significantly lower compared to the traditional map application. The authors observed ergonomic deficits as users simultaneously had to hold a tablet and interact with it. When given the choice between the prototype and the typical zoom and pan map application (static peephole interaction), users picked the latter, mentioning the fear of breaking the device and ease of use as reasons for their preference.

A more similar study to the horizontal peephole setting proposed in SPART, was carried out by Rohs *et al.* (2007). They tested map navigation using a phone's camera tracking either its position relative to a map or just with spatial awareness (without a printed map underneath). Both of these dynamic peephole interactions performed significantly better than the static peephole interaction enacted by a mobile phone with joystick navigation (Nokia N80) in a usability study with 18 participants who had to find the cheapest parking spot on a static map. Nevertheless, the dynamic peephole interactions suffered from technological setbacks (robustness of positioning) which underlines the technological challenges in providing a reliable dynamic peephole interaction (Rohs *et al.*, 2007).

Furthermore, in a study using projector phones to compare a spatially aware (thus dynamic) peephole interaction with a traditional tablet map application, Kaufmann and Ahlström (2013) found that, without previous usage training, a phone projecting only part of a global map that could be navigated by rotating the phone on its axis, performed just as well as classic pan and zoom applications in terms of efficiency with benefits for spatial memory. In addition, positive task performance was observed by Miyazaki *et al.* (2021) with minimal upfront training for classic (camera based) six degrees of freedom AR augmentation in a study with 13 participants in a map search task.

Finally, many commercial applications propose dynamic peephole interactions by using camera-based AR, the internal gyroscope or magnetometer of mobile devices to provide augmentations (*e.g.* for stargazing). These sensors provide sufficient angle accuracy for handheld augmentations (Hürst & Bilyalov, 2010). However, as pointed out in the introduction, these are inadequate for supporting collaboration, since they need to be held by one person and at a minimum distance from the augmented object.

In a nutshell, several studies have demonstrated the feasibility of a SPART-like interaction but its setup is neither portable nor affordable in the educational context, all while the little conducted research points towards benefits for collaboration. Therefore the research questions for the study of this paper, having previously developed a functional SPART prototype (Simon *et al.*, 2024) is: **Does a dynamic horizontal peephole interaction provide support for collaborative learning?**

3 THEORETICAL FRAMEWORK

Collaboration is a widely used term across different domains and consequently, visions of it differ. This section presents the underlying conceptual model of this study. By exposing the conceptual aspects and their behavioral cues, we can identify the interaction patterns in our data which are part of the collaborative learning process.

This paper is based on an extended definition of *collaboration* by Roschelle & Teasley (1995)***:*** ***Collaboration is a coordinated activity and a result of the intention to maintain a common problem perception in order to find a solution to a problem.*** This definition encompasses asynchronous collaborations and accounts for the difficulty to maintain a cognitively challenging exchange over a long period of time, resulting in "reflective pauses" during which participants do not actively engage in the main activity (Wise *et al.*, 2021). Indeed, collaboration is a dynamic phenomenon: Bigger groups dynamically split into subgroups and reunite to keep track on overall progress.

Collaboration, as a problem solving strategy, is deployed in both collaborative work and collaborative learning. Stahl defines ***Collaborative Learning*** as collaborative **meaning making** (developing a common understanding of a problem) and collaborative **knowledge building** (Stahl, 2021)**.**

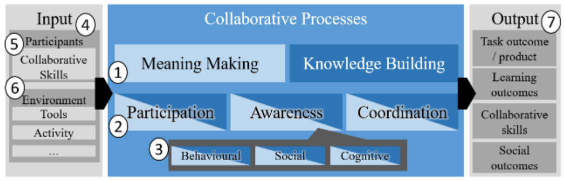

Figure 2: Collaboration model (Simon *et al.*, 2022).

Meaning making and knowledge building are parallel and intricate high level *processes* (figure 2:1). Effective knowledge building typically requires some initial shared meaning making, but the process of meaning making reappears throughout the activity and can be observed through interactions of questioning and explaining, or when a group decides to "go back" to discuss previous information (Clark & Brennan, 1991).

A central, observable process of knowledge building is transitivity (Vogel *et al.*, 2023). Transitivity refers to the ability of participants to not only understand another group member's idea but to actively build and develop those ideas with their own knowledge and resources.

On a lower level (figure 2:2), both meaning making and knowledge building require group members to **participate** and **coordinate** their contributions within the group and implement strategies to achieve or validate objectives. To do so, group members have to develop **awareness** of what their peers do, know and feel. Meaning making can indeed be seen as a process of building collective cognitive awareness (who knows what) and a shared understanding of the problem itself.

Awareness is not only required in establishing a common cognitive state of the group but also in determining social and behavioral group members' states (Ma *et al.*, 2020). Barron introduced the concept of a social space (relationships, social presence etc.) in addition to the cognitive space (holding a common perception of the problem and possible solutions) that has to be taken care of while collaborating (Barron, 2003). To that end, collaborative awareness processes, grouped into **social**, **behavioral** and **cognitive** processes (Ma *et *al.*, 2020) support both the relational and cognitive space, while being components of both meaning making and knowledge building (figure 2:3).

In order for those processes to take place, a number of behavioral and cognitive information has to be exchanged among participants, requiring active **participation** (the second process category in figure 2:2) of group members in the construction of both a social and cognitive space. The social space is nurtured by social-behavioral engagement, for instance "positive interactions such as respect and support for each other" (Isohätälä *et al.*, 2020). Participation targeting the cognitive space can be, for instance, observed through contributions such as stating hypothesis on how to resolve the problem or clarifications on the problem itself.

The third collaboration process category (figure 2:2) refers to **coordination.** It describes the ability of the group to develop, apply and revise solution strategies, also known as group processing (Johnson & Johnson, 2009) as well as self-organization. On an individual level, members have to time interventions, identify missing information and contributions have to be organized, classified and ranked to deploy successful group level strategies to achieve goals.

Together, the three main collaborative processes of **participation, awareness,** and **coordination** support meaning making and knowledge building (Mateescu *et al.*, 2019) and constitute cross-domain concepts of collaboration, that can be observed and evaluated during collaborative learning activities (Simon *et al.*, 2022).

As Dillenbourg (2001) points out, these collaborative processes do not necessarily emerge naturally within a group. They depend on collaborative conditions which can be considered as **input** of the collaborative learning process (figure 2:4). These input conditions consist of

- participants' existing *collaborative skills* (Hesse et al., 2015) (figure 2:5)
- the *environment* in which the *activity* takes place (figure 2:6)
- *tools* used by group members to accomplish the activity. Tools may or may not support successful collaboration. For example, some tools have been shown to introduce an additional cognitive load (Kirschner et al., 2018).

The concepts, presented above form a process-oriented collaboration model, are summarized in figure 2. In accordance to our hypothesis, we use this model to analyze the video material of the exploratory experiment presented in the next section.

4 METHODS

The following subsections describe the design of the learning activity and the SPART prototype in addition to the experimental setting and procedure.

4.1 Activity Design

The activity was designed in an iterative approach with a geography teacher in a French middle school. The content was created so that the activity would fit the current curriculum on tectonics.

Students had to investigate the movements of tectonic plates. In order to provide room for collaborative learning as defined by Stahl (2021), we structured the activity in several tasks with fading scaffold. We attributed students the role of research assistants of geographer Jason Morgan, presenting his theory of tectonic plates in 1967 at the national geophysical congress. Students were given data of ocean floor age and seismic activity graphs (figure 3) and the goal to provide Morgan with compelling evidence for the relative tectonic plate movements. In order to encourage collaboration, we intentionally integrated elements of positive identity interdependence (research teams), positive outside enemy interdependence (the backstory features Harold Jeffreys, a prominent critic of the tectonic plate theory), and an ill-defined problem ("find evidence to prove a theory").

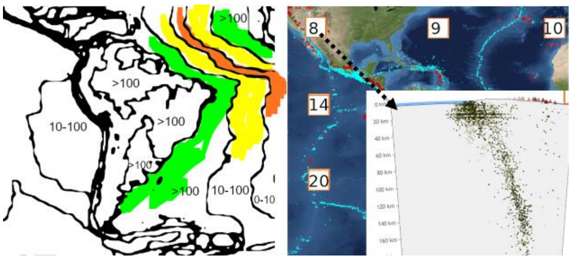

Figure 3: Ocean floor age overlay (basemap), partly colored (left) seismic activity overlay with profiles (right).

The activity was structured in four tasks: Initially, groups had to *read* and *understand* the assignment. The second task consisted of *coloring* the map depending on the ocean floor's age (figure 3, left). Thirdly, students explored the seismic graphs by *classifying* them depending on seismic intensity. Finally, students had to define the direction of the plates' movements and explain "incoherent" ocean floor data in front of the coast of Chile (old and recent plates side by side). For this to succeed, students had to digest hints, spatial data and emit *hypothesis* they would *validate* with the available data to provide Jason Morgan with a speech on evidence for the relative movement of tectonic plates.

Students were provided a static map containing the outlines of geographic ages, coloring pens and paper based vertical seismic data for a number of fixed positions (figure 3, right) alongside a map with the age of the ocean floor layers printed on it (figure 3, left). This data was also accessible through the tablet application. Students could therefore pick their preferred medium. Groups with the dynamic peephole interface (named "SPART" groups) had the layer map attached to a rigid support to provide accurate overlay (as in figure 4), whereas groups with static peephole interactions ("Control" groups) were given a tablet and the base map separately.

The application on the tablet provided two overlays that could be changed with the click on a button: one with numbers about the age of the ocean floor, and another with the seismic activities (see figure 3 right). On the second overlay, students could click buttons to get the vertical profile of seismic activities at the specific position (see figure 3, right). In the paper version, the vertical profiles' had to be looked up on another sheet of paper.

During the first two sessions, none of the groups managed to complete the activity. Consequently, we introduced additional hints in the task assignment.

4.2 SPART Prototype

In order to study horizontal peephole interactions on a static surface, we designed SPART, a system to augment any surface located under mobile devices (such as of-the-shelf smartphones or tablets). Among the various concepts, a mechanical prototype SPART-ME (50€ material cost, 02/2024) reached technological maturity first and was therefore used in this study.

The device consists of a frame for the smartphone or tablet to which are attached two strings. Attached to the support are two reels with potentiometers at two points outside the working area to measure the distance of each string to the device. The result of the mechanical trilateration is then sent by a Bluetooth enabled microcontroller to the attached device which can display the augmentation layer depending on its physical position. This version of SPART-ME can augment an A3 sheet with an average accuracy of 0,5cm and a refresh rate of 20Hz. The technical implementation is detailed in another article (Simon *et al.*, 2024).

Due to the strength of the string retraction mechanism, tablets and smartphones have to be held when far from the mechanism (increasing retraction force) in this version of SPART.

Figure 4: The SPART-2 group during the coloring task.

4.3 Setting & Procedure

This is a **comparative study** between four groups who have SPART (dynamic peephole interaction) and other groups, called Control, who have a tablet with the same information, but with static peephole interaction. In concrete terms, the SPART groups had to slide the tablet over a map to see the information, while the Control groups used swipe-like tactile interactions to move the map.

The study included a convenience sample of 32 students aged 12 to 14 in a public middle school in France. Students worked in groups of 4 in a classroom designed for natural sciences. Experiments were conducted in the end of November 2022. Group 1/2/4-SPART and 1/2/4-Control had 60 minutes, while groups 3-SPART and 3-Control only had 45 minutes due to lesson restrictions.

Group composition was orchestrated by the teacher in an effort to create homogenous groups in terms of task performance. 1/3/4-SPART and 1/3/4-Control were mixed groups (two boys, two girls). 2-SPART consisted of four girls while 2-Control consisted of four boys.

The classrooms, as illustrated in figure 5, are structured in work islands (figure5:3) that allow students (figure 5:8) to stand, or sit on elevated chairs. Students in this study were standing, aligned and facing one of two cameras (figure 5:1).

We filmed from two angles: One camera faced the group to capture facial and gestural expressions (figure 5:1) while the second camera targeted the table (figure 5:2).

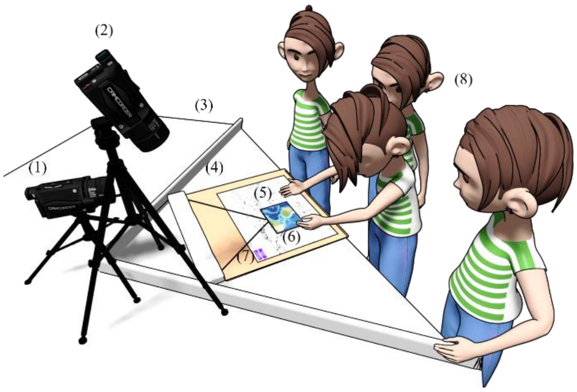

Figure 5: Cameras and experimental setup (SPART).

At the beginning of each experiment, participants were shown the functionalities of the tablets and given a short introduction to the activity.

Every group had a tablet, a copy of the task assignment with all map layers printed in color, as well as seismic data printed as graphs for specific locations (as in figure 3, right). All information was available as a paper version and on the tablets so students were free to use either or both in parallel.

At the end of the experimentation, students were asked whether the group had worked together before and about their perception of SPART in their work. Additionally, having identified one high-performing group, we interviewed the most engaged student on his experience during 30 min. During the interview, he was shown video extracts of the experimentation and invited to describe them before being asked more targeted questions (*e.g.* "What was your intention behind this move?").

5 ANALYSIS

In section 4, we highlighted the three central processes of collaborative learning, namely *coordination*, *awareness* and *participation*, (figure 2:2). Consequently, in this section, we analyze video material with a focus on these three processes. We then highlight contributions to the social space, as collaboration tends to fail without it (Bannon, 2006) (figure 2:3). Finally, we step up to the abstraction level of *meaning making* and *knowledge building* (figure 2:1).

5.1 Coordination

Among the eight groups, little coordination (*e.g.* changing strategies, searching for missing information), beyond linearly following the exercises, was found. 4-SPART was an exception and also the only group to correctly identify lateral and vertical tectonic plate movements as well as differences in speed (thus successfully completing the assignment).

4-SPART showed signs of awareness for the potential limit of time and tool access. Two students proposed to advance individually on follow up exercises during the coloring activity, after noticing that the coloring activity could be conveniently carried out by two students ("...You can be two at coloring together", *steps away from the table and joins partner in reading next task*). When stuck, the group decided to rebuild common ground by rereading the initial, global assignment and by reconsidering all previously collected evidence following suggestions of the interviewee. When the interviewee was asked about the early parallelization of work, he stated that he commonly employed the strategy in group works to "gain time". And that "there was not enough space for everybody around the table anyways". Among the other groups, such behavior was not observed.

In control groups and SPART groups alike, the tablet itself did not seem to play a major role for this collaborative aspect. SPART introduced a coordination difficulty for the coloring task. SPART groups that used the attached map for coloring, had to move the tablet out of its position were the age of the layer was indicated when coloring the underlying layer at the same position on the map.

SPART groups spent overall more time on the coloring and classification tasks compared to control groups, confirming the time overhead in the integration of the tool into the activity (figure 6). Consequently, those groups had less time for hypothesis building and validation, with the exception of 4-SPART, having spent significantly less time coloring than other SPART groups. This group used the separately provided, smaller map with the age of the ocean floor printed on it for coloring. Hence, the group did not have to move the tablet every time. Against our interpretation of a particular smart use of this alternate map, the interview revealed that the group initially thought that the map attached to SPART was present for illustrative purposes only. 1-SPART just marked the color of a layer with a stroke while using the tablet, before coloring the whole layer without using the tablet afterwards. This approach avoided the tablet being in the way of coloring (as encountered by 2-SPART and 3-SPART). The group however was not able to turn its approach into a time advantage due to meticulously coloring the entire map.

While SPART groups were slower in completing the tasks, there were little problems with the interaction itself. The interviewee described the interaction as "natural" and "simple to use".

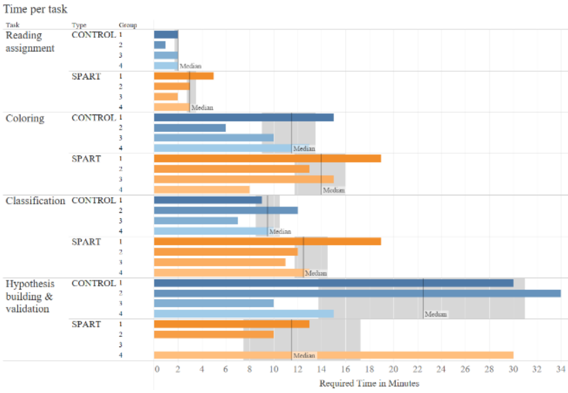

Figure 6: Time spent by SPART-groups (orange) and Control groups (blue).

Occasionally, users tried to drag the overlay with their fingers before remembering they had to move the tablet instead. The only difficulty that we noticed was that users had to hold the device in order to prevent it from sliding towards the reels. No considerable overhead in cognitive load was noticeable or reported.

5.2 Awareness

SPART seemed to work as a visual cue for group members engaging in personal work or activities unrelated to the main task. Indeed, having interviewed one of the 4-SPART students, the student outlined the role of SPART to follow his team member's activity at a distance, both during phases of cooperation and transition back to collaborative phases.

In 1-SPART, two boys got carried away by a discussion about computer games (figure 7). However, at least one of the two regularly had a glimpse at SPART. After twenty minutes, the two girls decided they had invested enough effort and ordered the boys to do the remaining exercises. Interestingly, the boys were aware of the exercises' results carried out by the girls and were able to conduct the following tasks without re-iterating over the previous work.

Figure 7: Girls working with SPART while boys converse off-topic (yellow: tablet position)

Inversely, in group 4-Control, monopolization of the device was an issue, since other group members temporarily couldn't follow one group member holding the tablet in his hands while walking around. Similar situations arose when members held the tablet (in control conditions) in a specific direction, thus blocking access of other members (2,3,4-Control).

In addition, we noticed that the strength of the SPART retraction mechanism required students to hold the tablet in position. While not ideal in tool usage, members helped each other holding the tablet in place and manipulating it conjointly. 4-SPART showed consistently recurring **behavioral awareness** as two or three members of the group interchangeably manipulated the tablet to move it into position, displaying profiles and changing layers.

Cognitive awareness was rare: Group members rarely referred to their peers' skills or knowledge. 4-SPART was an exception in a sequence where one of the boys (A) remembered a previous lesson and another group member (B) remembered that A had kept a cardboard model of a tectonic plate movement that they introduced to refresh and illustrate knowledge about tectonic plate movements.

Concerning **social awareness**, groups globally functioned well in terms of timing for oral interventions except for a member of 4-SPART who occasionally tried to contribute his ideas at the same time other members were talking. When he was the only one talking, peers sometimes did not react to his propositions or ideas.

5.3 Participation

In terms of oral contributions, we measured subject related utterances per group. 4-SPART had 30% more utterances than the other groups and balanced participation. 3-Control showed a fully asymmetric participation pattern in the first half of the experiment: only one person was working and monopolizing resources (tool access and space). Girls in 4-Control contributed considerably less than their male counterparts, both in terms of oral and nonverbal participation. The discrepancy in participation was accompanied by monopolization which manifested in one of the boys taking the tablet and interacting with it separately from the rest of the group.

Participation in 1-SPART and 1-Control was unbalanced: the first half was completely dominated by the two girls and the second half by the two boys. 2-SPART was characterized by participative symmetry but little oral contributions.

The overall median value did not significantly vary between Control and SPART groups.

In general, due to the limited space around the table, one group member was consistently limited in his/her access to the tablet (Control and SPART). In the interview, awareness for the lack of space and tool access was confirmed by the participant, adding "…it is important for everybody to equally access the tool, everybody should have a turn on it". Beyond awareness for the importance of equity in participation he stated that he takes an active role in regulating access by pointing out unbalanced access to resources. "This was not the case in this activity. I remember talking a lot, B talked a lot, the others were a little more passive, but I think everybody had the possibility to participate".

5.4 Socializing

We noticed asymmetric relationships in 3-Control, 2-Control, 1-Control and 1-SPART. All of them were present since the beginning of the activity, pointing to existing social discrepancies among students.

Student exclusions manifested in restricting member's tool access, especially in control groups by orientating the tablet away from a person.

4-SPART showed an intact social space: Members showed motivation, joked while staying task-focused or made fun of each other without demeaning overtone. In this environment fell the brainstorming phase about lateral tectonic plates' movements which resulted in the correct hypothesis (and its validation): Just before one of the students emitted the theory of subduction in front of the Chilean coast, the group at 52:43 was missing an appealing theory. Jokingly, another student says "the plates extend so much that it [the older, missing layer] has just disappeared!" other group members laugh, triggering hand movements of another student to mimic an explosion. Gesturing continues, this time his left hand slides from right to left (as the previous tablet movement) while he says, half seriously "it went underneath…", then exclaiming: "It went underneath!"

Interactions in 2-Control initially were characterized by task distribution by the dominant member, occasionally judging team members ("wait! you're sc*** it up!", "idiot" etc.) or restricting access ("Can I write?" – "No"). During the final phase, all members could propose their hypothesis, but no consensus (nor strategy to achieve one) was found to decide on one common theory. The group did not show transactive interactions or strategies to validate or falsify the hypothesis. The contribution of two students was restrained to reading the assignment. One of them stated that he "didn't understand any of this". His statement was not followed by other group members trying to explain the topic to him and his further interventions were limited to off-topic contributions. Good task performance of this group can be attributed to the good individual task performance of the dominant member and the person filming giving advice, which consisted of intermediate task validation concerning plate limits ("You're missing one") and correction at 30:09 as well as motivational speech at 47:44 ("you're nearly there, you are on the right track"). The intervention highlights the importance of strategically placed feedback on task performance and motivation, since the group itself did not provide positive peer feedback and exhibited asymmetric group relationships. Since this study was conducted in a classroom setting, teacher interventions also happened in 4-Control at 60m04. The teacher intervened based on the wrongly placed arrows for horizontal plate movement. 1-Control and 1-SPART assisted at a general intervention by the teacher having identified problems of other student groups finding tectonic plate limits and pointing students at seismic activity to correctly identify those limits.

5.5 Meaning Making

Groups had access to a paper version of all visualizations. However, in the case of SPART, all groups exclusively used SPART instead of the paper version throughout the experiment. In the case of control groups, the use of paper versions was more prominent. In one sequence, one member of 4-SPART moved the tablet in the direction of the South Pacific plate. Previously he had identified a "problem" in the data, consisting of the fact that the South Atlantic plate pushes in the opposite direction. The same person identified the lateral subduction movement ten minutes later. In general, SPART seemed to be the privileged way of exploring the available information.

5.6 Knowledge Building

The complete loop of emitting, discussing then testing and finally validating hypothesis could not be observed beyond the 4-SPART group. Tablets were however used as tools for attempted knowledge building in 2-control, 1- SPART, 2-SPART and 3-SPART. 3-SPART discovered a complementary feature (implemented and intended for scaffolding a group in case of difficulties) for displaying a gradient map of the ocean floor age on their own and used it to check their own coloring and movement hypothesis. This feature was later requested explicitly in the interview by a member of 4-SPART (who had not found it).

4-SPART used the possibility to display vertical profiles on the map extensively to check hypothesis (mountain chains among plate limits, subduction along earthquakes etc.). The following sequence is the sequel to the previous sequence illustrating the discovery of the subduction movement by 4-SPART:

A: "it went underneath!" […]
A: "that's why there are mountains!"
uses his hands as plates sliding one under another
B: *(slides tablet over Chilean coast with age layer overlay)* But look, there is no information at all? (points on tablet). I'm sure the plate is somewhere else".
A: "I'm sure this is it. See, there is a mountain chain"
B: "Yes that's maybe it?" *Students chatter indistinctly*
A: "Wait, wait, wait, my theory starts to strengthen"
Moves tablet over the sketched buttons to change the overlay to the seismic overlay with profile access, then slides it over South America, opens a profile on the Chilean coast.
A: "See, the line [of earthquakes in the graph]?"
B: "So the yellow [colored, recent tectonic plate] goes under the green [colored, older tectonic plate] …"
A: "That's why it disappeared."
C: "Strange. That would have resulted in…"
A: "And we could use that to support …"
Moves tablet to another profile icon, opens the profile
A: "…this. We can see clearly the line [of earthquakes descending in depth] there."
C: "But those are the earthquakes…"
A: "Exactly! When the plate moves, it creates friction. And thus earthquakes."

To illustrate and identify the speed difference between different plates, the group used a cardboard model from previous lessons.

Interestingly, even the colored map was only occasionally used by 4-SPART. Instead, group members used the tablet's white ocean floor overlay (see figure 4 left) containing the ocean floor's age in numbers. When asked about it in the interview, the interviewee explained it by the difficulty of having an additional level of abstraction ("I had to remember what the colors meant") that didn't seem to provide meaningful information to the group. Another mentioned advantage was the size of the overlay with more details that the A4 printed version this group used for the coloring task.

6 RESULTS

Having presented our observations on the collected eight hours of dual-perspective video material, we present, in the following sections, our interpretation of the role of SPART for the observed collaborative sequences during group work.

Initially, we examine the role of SPART for collaborative processes identified in section 6.1-6.3 (figure 2:1,2). We further explore its possible impact as a memorization and communication support before hypothesizing its role as support to learn how to collaborate and its induced cognitive load. Finally, we discuss the activity design and possible improvements.

6.1 The Role of SPART

The following subsections describe the possible role of SPART for collaborative processes (awareness, participation and coordination) from the tool perspective, based on the observations presented previously, and its potential beyond this study.

6.1.1 Awareness, Coordination & Participation

Our analysis points towards **SPART supporting behavioral awareness processes and collaborative group dynamics.** Indeed, SPART seems to enact a visual anchor for other group members, both in synchronized collaborative sequences, as well as in settings with subgroups or reflection phases. The tablet's position allows to deduce roughly on what parts the rest of the group is working. On several occasions, we observed students engaging in off-topic conversations and seamlessly picking up their peer's work.

We further observed the fact that **SPART seems to reduce tool monopolization** by one member because it is functionally bound to the surface it is placed on. Students in the control condition made use of the freedom the tablet provided to carry it around and introduced monopolization by a single student.

We could not find evidence for support on other collaborative dimensions such as coordination or collaborative conditions. If increased awareness led to increased participation or coordinative efforts, this was not noticeable.

6.1.2 Communication Support

Our observation leads us to believe that SPART could support **nonverbal communication**. Indeed, location and movement of the tablet communicate meaning. The position shows the current working area of the group. Moving the tablet underlines the user's intention and ideas on task hypothesis, validation or information retrieval. This hypothesis was strengthened by interactions during the moment 4-SPART verified and validated the subduction hypothesis (and preceding exercises: identifying limits of tectonic plates, speed of moving plates and hypothesizing about vertical movements). The conversation sequence illustrates the role of nonverbal communication assisted by the visual aid SPART provides. The particular context of tectonic plates would be an interesting topic for a study on the nonverbal affordances of a rigid body force simulation for nonverbal communication in SPART to confirm the importance of nonverbal communication for collaboration.

6.1.3 Memorization Support

SPART's particular advantage seems to be the **link between location and information** (*e.g.* for fast access of profiles as shown in figure 4). Literature suggests that its appeal is rooted in the spatial and gestural memory that the interaction draws on (Kaufmann & Ahlström, 2013). Once adopted, information retrieval is fast and focused. As such, it seems particularly useful for use with maps or high-level visualizations.

Association of information to locations is used in other contexts such as techniques for enhancing memory capacities (mnemonics): McCabe (2015) has shown the beneficial use of maps for building high capacity mental structures (mind palaces). Such an approach could benefit collaborative activities in the educational sector. We noticed students having forgotten previous lessons on geography who consequently were disadvantaged in the activity. If content can be delivered through collaborative mind walks, this might benefit individual memory retrieval as shown by McCabe (2015). SPART can assist mind walks by providing access to collaborative artefacts created during previous collaborative activities (photos, sketches *etc.*) tied to the exact map position for better recall performance (contextualization).

The second distinctive feature SPART allows for are **overlays, fitting the physical layer**. While this can be achieved with multiple views of the same, printed map, having just a partial overlay in form of a tablet that can be easily moved, increases practicality. Students used and asked for the possibility of intermediate visualizations. In a previous workshop with K12 educators, educators noted the potential of SPART for students to access as many intermediate visualizations between abstraction (*e.g.* a map) and reality as necessary to improve their map reading skills. This aligns with the spontaneous suggestion of our interviewee wishing for a gradient map and 3-SPART exploiting the feature.

6.1.4 Learning to Collaborate

Based on some limitations of SPART, such as the strong retraction mechanisms (pulling the tablet back when too far from the mechanism), we see potential for gesture based collaboration, requiring the joined engagement of multiple users to use a functionality and consequently increase overall participation (activities which physically require all members to participate through **positive interdependence**), coordination (physical coordination required) and awareness (Morris *et al.*, 2006). Such collaborative activities could be destined to raise explicit student awareness (meta-awareness) on the functioning and importance of collaborative processes and skills.

6.1.5 Reduced Cognitive Load

While **cognitive load associated to the tool use seemed low**, it still adds to the collaborative cognitive load required for the activity. Students already overwhelmed or missing collaborative skills did not benefit from the introduction of SPART.

Groups with collaborative skills and solid knowledge on tectonics seemed to benefit from the use of SPART, while groups lacking organization and collaborative skills could not overcome those shortcomings with SPART.

This confirms the general consensus that a tool can enhance collaboration but that it is not as important a ***condition*** for successful collaboration as collaborative skills and an open and productive social environment. SPART however is an interaction type.

It can be used in conjunction with the majority of existing collaborative functionalities that have been developed for tabletops (task related or to regulate collaborative processes directly), all while providing a large and mobile work space with a convenient way of accessing virtual content (Simon *et al*., 2024).

6.2 Activity design

The activity design is the result of a collaboration between the teacher (and his constraints to teach the topic) and our work group (with the goal to create a purposeful use of SPART). The coloring and classification task are examples of the pedagogical dimension guiding students towards the understanding of tectonic plates. If the activity was to be redesigned, the coloring task and classification would probably be compressed into a virtual, automated coloring activity where students could freely pick a color scheme of their choice and autofill the ocean floor layers or keep the original map in order to foster coordination and discussion rather than cooperative coloring.

7 LIMITATIONS

The study was carried out in **varying conditions**. 1-SPART and 1-Control worked in the classroom alongside their classmates, whereas [2-4]-SPART/Control where placed in empty classrooms to improve sound recording quality for analysis. In addition, 3-SPART and 3-Control had only 45 minutes compared to 60 minutes for the other groups. Since students knew each other, they had predefined relationships which impacted their group behavior. Camera (wo)men interacted with students and some groups received advice from the teacher.

Furthermore, **available desk space was insufficient** for four students. Tensions may have arisen from the difficulty to work around the tablets. The prototype, physically linking the tablet to the surface, limited possible interactions (string retraction force). In addition, the activity design naturally centered the hypothesis building task around one part of the map, thus favoring interaction with SPART for the person standing at this position.

Interviews with all groups would have provided a more comprehensive view on internal processes than the single interview but could not be conducted due to time constraints.

Finally, video material was **analyzed** by a single researcher, who also conducted the subsequent interview, thus exposing him to confirmation bias during the questions.

8 CONCLUSION

In this comparative study, we explored the impact of the dynamic horizontal peephole interaction SPART on collaborative learning.

Previous research on dynamic peephole interactions is scarce due to technological challenges and high costs.

The study was conducted in a French middle school with 32 students and a subsequent sequential analysis. We presented our observations and interpretation on the role of SPART for the collaborative processes of *awareness*, *participation* and *coordination* and higher level processes such as *meaning making* and *knowledge building*.

The results point towards benefits for awareness for high performers and SPART being a support for knowledge building. SPART seemed to draw low cognitive load among users, was robust and natural to use. It provides a collaborative and mobile platform. A number of interesting perspectives for future investigations have been identified: support for mind walks, increased task awareness and learning of collaboration.

Low device cost (50 €) and portability in the latest prototype versions open the door to large scale experiments and potential future adoption beyond the educational sector. Experiments are underway to confirm this study's findings in mobile setting.

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