The Benefits and Limitations of Distributing a Tangible Interface in a Classroom

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Abstract: We report the design and testing of TapaCarp, a CSCL environment for carpenter apprentices. From the start, we designed TapaCarp for a classroom usage. This led to an interface distributed over several components and modalities. A first user study conducted in a classroom environment and involving 24 carpenter apprentices produced mixed conclusions about the distribution of the interface. On one hand, it proved suitable in terms of classroom integration and flexibility. On the other hand, it hurt usability, both at the group level and at the classroom level. Based on these results, we discuss the relevance of distributing a learning environment interface and introduce the concept of "over-Hutchins threshold", a point after which the distribution of the interface becomes harmful to classroom orchestration.

1. Introduction

Classroom orchestration has been a rising topic in the CSCL community in the last few years (Dillenbourg, Järvelä, & Fischer, 2009). A core idea of classroom orchestration is that bringing learning technologies to the classroom should accommodate the many constraints of classroom management, including practical constraints (time, discipline, etc.). These constraints have often been somehow neglected in CSCL either because studies where conducted in labs or because technologies were designed to be used 'anywhere'.

Our recent work has focused on designing technology for face-to-face learning in the classroom. To design for the classroom, we consider both the *intrinsic* pedagogical constraints that make for an effective learning tool (how people learn, who is the audience, what are the content features) and the *extrinsic* constraints that come with the deployment of the learning environment in the classroom (time, discipline, teacher's energy, space, etc.). In this article, we describe how we created TapaCarp, an augmented reality environment for the specific context of a classroom of carpenter apprentices attending a vocational school.

With other tangible interfaces we tested in vocational schools and elementary schools, we found paper to be a specific type of interface that fits particularly well within classroom practices. Two decades ago, Hutchins (1995) provided an explanation of why paper was surprisingly useful in an aircraft cockpit, which is a supposedly high-tech environment. According to him, the two pilots and the various artifacts spread over the physical cockpit environment form a distributed system in which information flows across different media. A classroom is a more diverse environment than a cockpit, but Hutchins' analysis is nonetheless relevant for the classroom. We therefore used it while designing TapaCarp and to interpret the data collected during the deployment of Tapacarp in a classroom.

TapaCarp is the result of an iterative design process conducted with a teacher and his students over two years. Our continuous attempt to integrate the environment into the classroom life led to a highly distributed interface. We could even call it a 'scattered' interface: the learning activities imply interactions across five different modalities: tangible wooden blocks, paper cards, paper sheets, digital augmentation and even sometimes a computer mouse. Conceptually, with such a scattered interface, the environment does more or less disappear as one environment; it somehow 'molds' into the classroom ecosystem. Practically however, we found that distributing the interface too much leads to usability issues, both for the teacher and for the learners.

We first describe the context of carpenters training and the interface that resulted from participatory design. Second, we present the results of a study conducted with three classes. Finally, we discuss the concept of distributed interface and the tensions that can appear between the individual usability and the 'orchestrability' of the classroom, which Dillenbourg defined as the first and third circles of usability (Dillenbourg et al, 2011).

2. The design of TapaCarp

Context

This work focuses on carpenter apprentices, (mostly male) students aged between 16 and 20. They follow a dual system, which means that they work four days a week in a company and go to school for the remaining day. Carpenter apprentices were chosen for 3 reasons: (1) CSCL work on young adults other than university students is rare; (2) carpentry involves hard 3D reasoning skills that are challenging for apprentices; and (3) we wanted to see if the tangible-paper distributed approach we successfully tested with logistics apprentices (Zufferey, Jermann, Lucchi, & Dillenbourg, 2009) would be relevant in a different professional domain. After visiting five companies and following the apprentices at their workplace as well as at school, we identified three main topics in which carpenters need to be trained: the law of statics for building, spatial reasoning skills, and building physics (sound/heat/humidity/insulation). This study focuses on spatial reasoning skills, which carpenters typically develop through drawing classes. Learning the practice of drawing is controversial in the carpenter community. Although the school curriculum for carpenter apprentices allots 3 hours of drawing classes per week for 3 years, at their workplace it is their superiors that draw the roof structures and not the apprentices themselves. In fact, most of the time the plans are not drawn by hand anyways but instead with CAD software. Our research addresses this tension between the needs of the companies and the practices at school: Could apprentices develop the spatial reasoning skills they need at work in a more efficient way?

Blocks and Cards

Our learning environment, TapaCarp, runs on the Tinkerlamp, a camera-projector tabletop system (see Figure 1, left). The projection area has a dimension of 70 by 50 centimeters. The system detects objects equipped with fiducial markers and provides visual feedback through the projector. This environment is designed for teams of 2 or 3 students seated around the table on which the lamp sits.

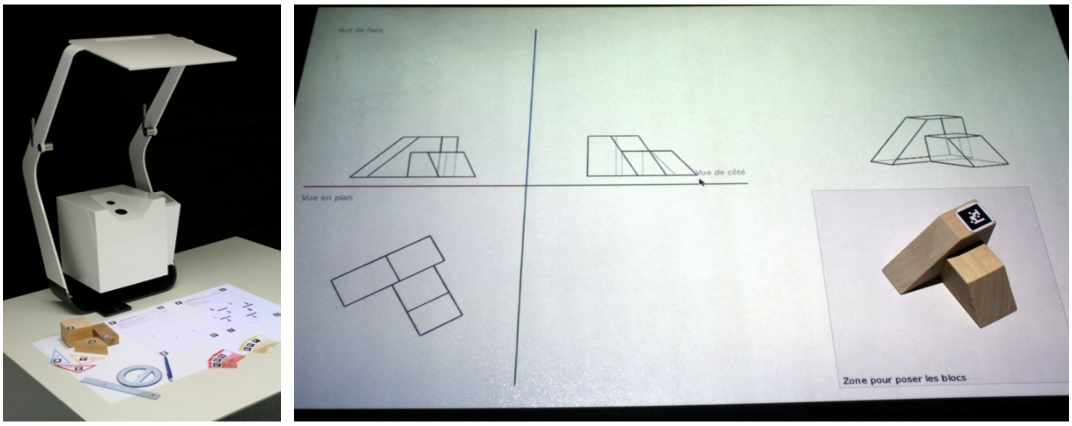

Figure 1. The Tinkerlamp (left) and the layout of TapaCarp (right): the wooden block and a perspective representation of it, as well as the three orthographic projections of the block.

TapaCarp is a collaborative learning environment that has been iteratively designed with the assistance of a carpentry teacher and his students. The teacher's main complaint about his students was that they did not make the link between the 2D representations of an object (its orthographic projections) and its 3D shape. This leads them to draw plans that are wrong, i.e. correspond to unbuildable roof structures. According to the teacher, students tend to follow descriptive geometry "recipes" to draw their plans, without understanding the link between the orthographic projections that they are drawing and the final object that they mean to represent.

The interface of TapaCarp is distributed over several components. The first component is a set of 3D wooden *blocks*. The blocks are equipped with fiducial markers (Figure 2, left), which allows Tapacarp to track their position and orientation accurately. Knowing the topology of a block, TapaCarp displays its orthographic projections and a perspective view of the object (Figure 1, right). The 2D and 3D representations are dynamically linked, allowing the users to explore the 2D-3D relationship by moving the blocks and seeing the effect of the movements on each view. The blocks serve both as an external representation of the drawing and as input for the system. Using tangible blocks that have the same geometrical shape as the digital object that they represent has been shown to be beneficial for learning (Cuendet, Bumbacher, & Dillenbourg, 2012).

While blocks are the core manipulation handles of the interface, they do not allow the users to trigger specific actions such as "launch activity 1", or "show feedback". We therefore introduced the second component of the interface: a set of papers *cards*. Cards are used to issue actions or to change options such as to launch an activity, to check the correctness of a solution, to ask for help, and to change features of the display. Each card has only one function and the number of functions provided by the system is therefore proportional to the number of cards available. This makes it easy to adapt the number of features to the students' level of expertise: the teacher simply gives them the appropriate set of cards. Cards were also chosen for practical reasons, such as their ease of distribution, storage, and sharing, all of which go in the direction of reducing the global orchestration load faced by the teacher. They are easy to manipulate and share between several users. This opens up possibilities for role taking (Burton, Brna, & Treasure-Jones, 1997).

A third component of TapaCarp is a standard computer mouse that was used to interact with the digital models. We do not have as a principle that modern interfaces should avoid using traditional computer input devices. Instead, we are looking for the most appropriate artifact for each type of interaction. In previous usability tests, which compared the mouse to tangible 'selectors', the mouse proved to be the fastest and most accurate tool to select a thin line on the views projected on the table.

Activity booklet and drawing tools

Based on the blocks and cards interface, we developed a series of learning activities to help apprentices learn to link the 2D and 3D representations. For instance, one activity was the following: given an edge shown on the 3D representation, the students had to identify it on the three orthographic projections. Another activity asked the student to place and orient one or several blocks based on two of the three orthographic projections. The activities could be completed in a short amount of time (less than 5 minutes). Their level of difficulty was adaptable by selecting simple versus complex blocks.

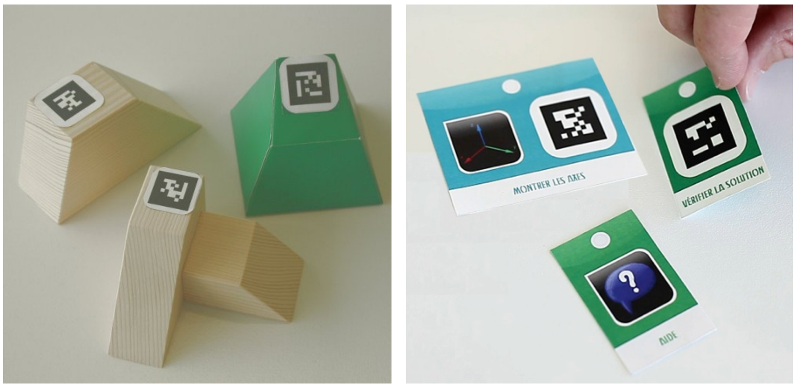

Figure 2. The blocks (left) and the cards (right) used to command the system.

Although the teacher had participated in their design and testing, he did not want to use them "for real", i.e. as genuine classroom activities, because the activities were not part of the regular curriculum. This came as a surprise, since TapaCarp activities and the ones done routinely in the classroom had the same goal (improving the 2D-3D link), an observation that the teacher did not refute. The major issue was that the professional and school environments of a carpenter are deeply embedded with paper and drawing, and that TapaCarp used neither paper nor drawing tools. Drawing-based practices are the DNA of these classrooms.

We therefore added a new interface component a *paper activity booklet* (Figure 3, left), so that students could perform the act of drawing on paper. They drew with their *regular drawing tools* (Figure 3, right), which further satisfied the teacher – learning to use those tools properly is a curriculum requirement. The booklet was composed of A4 pages, each page being a separate activity and equipped with a fiducial marker so that the system could augment it with instructions and feedback. New activities were designed to make use of the paper and drawing tools. In the end, except for the presence of the block and the possibility to augment the paper with the projector, the activities were very similar to the ones done in the regular curriculum.

This booklet and the set of tools constitute respectively the fourth and fifth component of our distributed interface. In fact, the tools are not properly speaking part of the interface – they are not tracked by the camera and are hence not an input device – but the same fiducial markers could be used for instance, to check if the center of a protractor is accurately placed in the center of an angle to be measured.

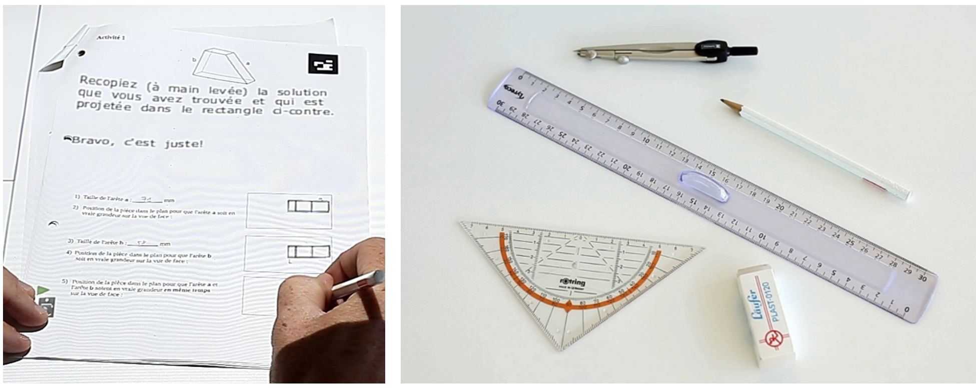

Figure 3. The activity booklet (left) and the regular students' drawing tools (right).

While it met the teacher's requirements, introducing the activity booklet had a side effect: the use of TapaCarp became closer to the usual classroom pedagogical structure, and more scripted. Each activity was now designed as a step-by-step process through which the students were guided by dynamical instructions projected by the system, as can be seen in Figure 3 (left). It is this final system that was tested in a classroom environment. We were closer to the teacher's needs but further away from socio-constructivists principles.

3. User study

Evaluations of TapaCarp were conducted in a classroom in one vocational school over three days. The class was split into two halves: half of the students attending the normal class with the teacher, while the other half used TapaCarp under the supervision of one researcher acting as the teacher. Ideally we would have liked the teacher to give the class with Tapacarp, but practical constraints made it impossible (someone had to take care of the other half-class). The goal of the 1.5 hours lesson was to teach the apprentices how to find the true size of an object from its orthographic projections. This is one of the key tasks in the 2D-3D passage. There are various techniques to find the true size of an object from its orthographic projections, but carpenters mainly use the rabattement technique, introduced by Monge (1798) and graphically explained in Figure 4. This technique and descriptive geometry are important subjects not only for carpenters, but also for many other professions such as mechanical engineers, architectural draftsmen, and even dentists (Sheryl Sorby, 2009).

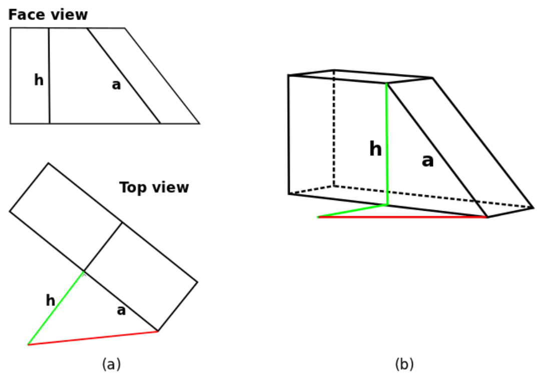

Figure 4. (a) The rabattement technique on 2D projections: to find the true size of the edge *a* by rabattement, one typically takes its height *h* on the face view and report it perpendicularly on the top view; the true size is then the red line. (b) A 3D representation of a rabattement.

3.1. Participants and procedure

Apprentices used TapaCarp in pairs. The activities had been designed together with the teacher. There were 11 activities presented in an increasing level of difficulty and grouped in three parts. All of them included exercises around the notion of rabattement: the first part (activities 1-3) was an introduction to the principle of rabattement; the second part (activities 4-6) dealt with finding the true size of an edge; the third one exercised finding the true size of a face (activities 7-11). The apprentices were all males aged between 17 and 31 with a mean age of 19. A total of 24 apprentices (12 pairs) used TapaCarp for 1.5 hours.

The blocks, the cards, the paper tools, and the activity booklet were provided to the apprentices. They were also asked to use their own regular tools: pencils, a ruler, a protractor, an eraser, and a compass. None of the activities required the mouse, which was hence not included for the study. In total, six blocks were given to each group. Each activity made use of one block. All the material was given to the apprentices at the very beginning of the class, except for three cards managing the animated feedback: These were given to them after they completed activities 3 and 4.

The data used for the analysis of the results were collected through the log files of the application, a questionnaire given to the students at the end of the experiment, and video recordings.

3.2. Results

One frequent concern with learning technologies is how fast students learn to use them. All apprentices were shown a short demonstration of TapaCarp (less than 5 minutes). To reduce the novelty effects that could distract them from the activities, the apprentices were allowed to play with the system for as long as they wanted before starting the activities. They typically tried the system for 2-3 minutes before starting the activities, and completed the activities for the remaining time within the 1.5 hour allotted.

Users feedback

We gathered both formal (written questionnaire) and informal (class discussion) feedback from the users. The questionnaire included 13 assertions to be assessed on a seven-point Likert scale, and 5 more open questions. A large majority of apprentices (18) had positive opinions, 2 were neutral and 4 were negative. From the 4 negative ones, most of the criticisms came from the lack of accuracy of the projection due to some calibration inaccuracies between the camera and the projector. The students were enthusiastic about the system, both in terms of perceived usefulness of TapaCarp for their training as well as in terms of its usability. For instance, they were interested in using TapaCarp more often (0.96 on the Likert scale) and said TapaCarp helped them understand the rabattement better (1.25). Only three apprentices said TapaCarp did not improve their understanding of the rabattement, out of which two said that they had already understood it beforehand. The animations were deemed especially useful to better understand the rabattements (1.95).

Left-right differences

The manipulation of objects by the two users reflects the asymmetry and the modularity of the interface. Figure 5 shows the number of activities in which the user on the left or right of the workspace performed an action or manipulated an object. There was a significant difference in the usage of the modalities: the participant to the right manipulated the blocks more, while the left participant used the cards more. Part of this asymmetry can be explained by the physical placement of the manipulation zone of the blocks (on the right). However, the cards could be used anywhere, so the fact that they were used mostly by the left participant is more surprising. These differences in the usage of the interface did not lead to different learning outcomes ($F[1,22]=3.54$, $p = .07$), although in 9 groups out of 12, the post-test score of the apprentice sitting on the left was higher than his colleague's.

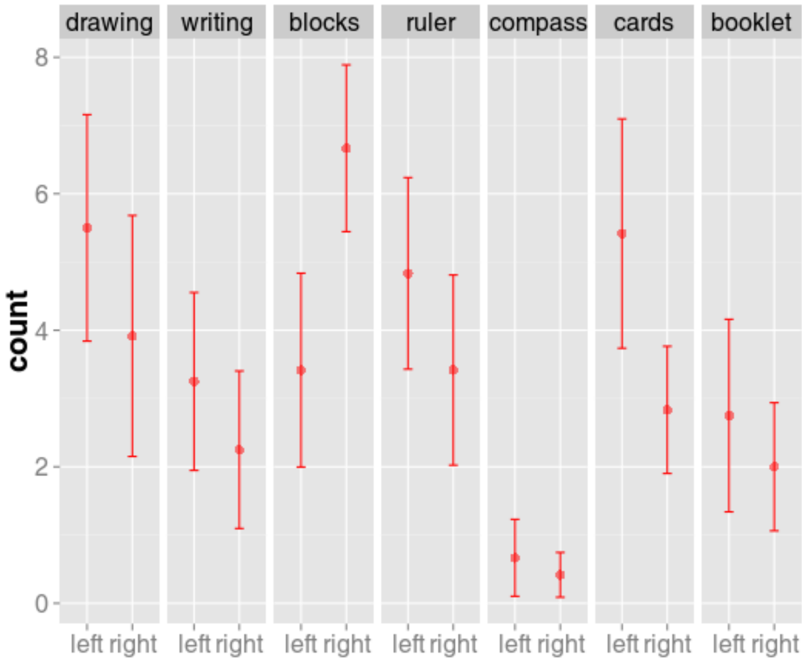

Figure 5. Average number of activities (with standard errors) in which each student on the left or right performed an action or manipulated the objects at least once.

Blocks and their interaction with the paper and tools

None of the groups tried to use the wrong block for an activity, most likely because a perspective view of the block was printed at the top of each activity page. The blocks serve both as manipulation handles and as an external representation. The apprentices' behavior showed that they understood this, and that they made the link between the 3D block, their drawing, and the projected representations. They used the blocks extensively to take measurements, check their solutions, or change the angle of the displayed projection. They measured dimensions both on the block and on the orthographic projections, and laid the block on their drawing to check that the length of an edge that they found by rabattement actually matched the real length. One could say that some of them even understood all too well how to use the blocks, since they sometimes used it not only to check their solutions but to find the solution by measuring the true size of an edge or face directly on the block instead of finding it by rabattement.

Usually, carpenter apprentices do not dispose of the physical model of what they are asked to draw on paper. Our activities forced them to link the actual block to the drawing. This link between the block and the drawing was done either directly by laying the block on the drawing, or indirectly by taking measurements on the block and reporting them on the drawing. Noteworthy is the fact that some groups did not make a direct link between the blocks and the paper and always used an additional tool – ruler or compass – to make this link. Others, on the contrary, used the block directly by laying it on the drawing.

Activity booklet

The activity booklet had a good 'orchestrability': easy to distribute and gather, no ordering problems or loss of activities. The apprentices are used to receiving exercises this way and did not question it. The navigation between the activities was not programmatically enforced, allowing students to browse through all the activities without any mandatory checkpoints. This resulted in some students not calling the teacher when the written instructions asked them to (so that the teacher could check their solution and give them more cards). A minor issue was that after completing several activities and flipping the pages, the stapled corner of the page was higher than the other ones, leading to some misdetection of the fiducial marker. This could easily be fixed by placing additional fiducial markers on the page.

Other observations

The augmentation of the paper with dynamic instructions and feedback generated a split attention effect. Some basic instructions had been printed on the paper to help students complete the sheet in a structured way. The dynamic instructions were projected on the top of the page. However, despite the flashing of a bright color the projected instructions were sometimes ignored. When they were stuck and asked for help, the teacher simply pointing to the instructions often solved the problem.

Each group received a total of ten cards and six blocks. These came in addition to the drawing tools and the activity booklet, and resulted in a large number of objects to manage on the tabletop. It was sometimes complicated for the students to find the card they were looking for; in some instances, a card was activated by mistake. Although students did not complain about that in their feedback, this appears to be a usability issue. From the orchestration point of view, the instructor had difficulties distinguishing what activity the students were working on from a distance, because the table was so cluttered with objects.

The experiment was not focused on learning outcomes. Actually, the cognitive activities we designed were not optimal and the learning gain in the context of this study was rather modest (4%). Experiments focusing on the evaluation of the learning gain from using TapaCarp have been reported elsewhere (Cuendet, Bumbacher, & Dillenbourg, 2012; Cuendet, Jermann, & Dillenbourg, 2012). The focus of this article is to investigate the usability of a distributed interface in a classroom environment.

4. Discussion

TapaCarp was designed with the constraints of the classroom in mind. The interface needed to be easy to use and robust to potential mishandling by new users. This led to a first version of the system with two modalities: the blocks as the main items of the interface, and cards to control the flow of the activities. Then the system evolved towards a more complex interface including three more modalities: a paper booklet, the mouse and drawing tools.

In terms of usability, the results of the field study were globally positive. With just a few minutes of introduction to TapaCarp, the students were able to use it to complete complex activities. Their feedback, although it must be taken with a grain of salt in light of the novelty effect, was positive both on the perceived usefulness and on the global usability of TapaCarp. The distributed interface allowed it to mold into the classroom ecosystem by using some of the media traditionally used in the classroom (paper and drawing tools). TapaCarp also allowed the students to work as usual on a tabletop and to keep their habit of working in pairs.

Another positive aspect of the distributed interface was that it fostered the emergence of roles within the pairs. Typically, while one student manipulated the cards, the other manipulated the blocks. On several occasions, one student prompted his partner with phrases such as "OK, we're good, now you can use the card to go to the next step". Role distribution in collaborative learning can be beneficial to learning (Burton et al., 1997) and has the advantage of engaging both students in the pair. In the case of tangible interfaces, where the "manipulation temptation" has been shown to be counter-productive to learning (Do-Lenh, 2012), paying attention and controlling who is manipulating what and when is especially important.

The positive aspects of a distributed interface in the classroom should not prevent us from seeing its limitations. We describe the limitations that we have observed in the next section.

Limitations

From its original orderly distributed configuration, the TapaCarp interface became over-distributed with its components being spread out all over the place without much order. This can be observed in Figure 6: on the left side of the lamp there is a ruler and a setsquare. On the right side, one can distinguish another setsquare, the six blocks, and an eraser. Close to the students' arms are the cards, the compass, as well as some pencils and pens. With all the objects added across the four modalities, the final interface represented a total of twenty objects. We analyze the impact of the distributed interface on the usability by using the three levels of usability linked to the classroom orchestration theory (Dillenbourg et al., 2011).

- Individual level: as mentioned earlier, there were no major usability issues at the individual level.
- Group level: During the study, we observed that the large number of objects led to some usability issues at the *group level*, although the students did not explicitly complain about it. The issues arise mainly from the cards, which students either unintentionally activated or, in some case, had trouble locating. For example, the "next" card was unintentionally pushed under the projection surface – and therefore activated – which led to a rapid "completion" of the activity that was not planned by the students. On several occasions, the students wanted to ask the system for help and had to look for the "help" card because it was hidden under the activity booklet or another card, or behind a block.
- Class level: The number of objects also reduced the teacher's *awareness* of learners work by making it difficult for him to see what group was working on what activities from a distance. This increases the teacher's orchestration load (Dillenbourg, 2013), namely the effort to assess the progress of each group.

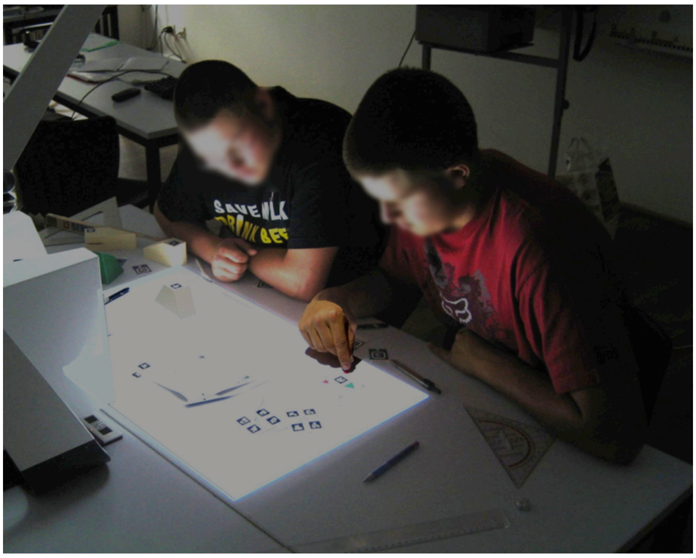

Figure 6. A group of students working with TapaCarp. One can see the various modalities: the drawing tools in the foreground, some cards close to the students' hands, and the blocks in the background. One block is active, and the students are reading off of the activity booklet.

While it had some positive impact, the distribution of the interface also led to some usability issues. The impact of the distributed interface on classroom orchestration can be better understood in the light of the four following design principles of classroom orchestration (Cuendet, Bonnard, Do-Lenh, & Dillenbourg, 2012): integration, flexibility, awareness, and minimalism. The distribution of the interface stemmed from a need to *integrate* into the classroom environment – the activity booklet and the drawing tools were included on the teacher's request to fit in the classroom. The resulting *flexibility* is also increased: it is easy to add/remove part of the interface depending on the level of students, or to distribute the interface over three students rather than two if a class has an odd number of students. The usability issues described for the group level can be interpreted as a lack of *minimalism* in the design of the interface. As for the usability issues at the class level, they were directly linked to the lack of *awareness* resulting from the clutter of objects on the table.

Hutchins exposed how the distribution of information could help a cockpit remember its speed (Hutchins, 1995). Similarly to Hutchins' approach, we developed a learning environment in which the interface is distributed across several modalities and media. Hutchins' analysis of a cockpit assessed the distribution of information as positive. In our study, we witnessed that the distribution of the interface has potential benefits, but also that over-distributing the interface can lead to a usability reduction on some of the three usability levels. The question that begs an answer is: how many objects can a distributed interface have without hurting usability? In other words, could there be a point, which we could call the "*Hutchins threshold*", beyond which distribution of the interface could be harmful? In reality, Hutchins neither claimed that an interface should be distributed, nor how much it should be distributed. As a tribute to his work, we simply use his name to discriminate the point where the advantages of distributed may be counterbalanced by the shortcomings.

We do not have an answer to this question. This threshold is not simply a number of objects, it also depends on the characteristics of the objects: how much space they occupy on the interaction surface, how easily they can be stacked, sorted and put away, how often they are moved unintentionally (e.g. because they are too light), etc. It would take many carefully designed experiments to answer it in the case of TapaCarp. What we observed in the user study is that some distribution of the interface increased collaboration and decreased the orchestration load, but that a higher degree of distribution hurt the usability of TapaCarp and increased the orchestration load. While it is doubtful that there exists a general theory linking the number and type of objects in a distributed interface with the collaboration and orchestration loads, we believe that the degree of distribution of an interface is worth considering when designing a learning environment for the classroom.

For example, in TapaCarp, it is mainly the cards and the blocks that brought TapaCarp beyond the Hutchins threshold and caused the decreased of usability. It may be that reducing the number of cards and blocks needed simultaneously would solve the usability issues. This can be achieved by placing only the objects needed for the current activity on the tabletop. The cards could, for example, be bundled with the corresponding activity sheet, while the blocks could be stored in a corner of the classroom where students could go to pick up the block corresponding to their current activity.

5. Conclusion

The approach presented for the design of TapaCarp is distinctive in that we sought from the start to design TapaCarp for a classroom usage, and that it led to a distributed interface. Following the observations of the user study, we discussed the benefits and drawbacks of a distributed interface for a learning environment. On one hand, distributing the interface proved suitable in terms of classroom integration and flexibility. On the other hand, it hurt the usability of TapaCarp, both at the group level and at the classroom level.

We see great potential in distributed interfaces for learning environments. However, over-distribution may hurt usability, and to this end we introduced the concept of the "Hutchins threshold", a point at which the distribution of the interface breaks one of the five principles of classroom orchestration design. We do not claim that the Hutchins threshold can be computed and will hold true invariant of the conditions. Rather, we see it as an important design concept to keep in mind when designing tabletops and tangible interfaces for learning.

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