Tangible Paper Interfaces: Interpreting Pupils' Manipulations

Quentin Bonnard, Patrick Jermann, Amanda Legge, Frédéric Kaplan, Pierre Dillenbourg
CRAFT, École Polytechnique Fédérale de Lausanne
{first.last}@epfl.ch

ABSTRACT
Paper interfaces merge the advantages of the digital and physical world. They can be created using normal paper augmented by a camera+projector system. They are particularly promising for applications in education, because paper is already fully integrated in the classroom, and computers can augment them with a dynamic display. However, people mostly use paper as a document, and rarely for its characteristics as a physical body. In this article, we show how the tangible nature of paper can be used to extract information about the learning activity. We present an augmented reality activity for pupils in primary schools to explore the classification of quadrilaterals based on sheets, cards, and cardboard shapes. We present a preliminary study and an in-situ, controlled study, making use of this activity. From the detected positions of the various interface elements, we show how to extract indicators about problem solving, hesitation, difficulty levels of the exercises, and the division of labor among the groups of pupils. Finally, we discuss how such indicators can be used, and how other interfaces can be designed to extract different indicators.

Author Keywords
Paper interface; Manipulation; Computer Supported Collaborative Learning;

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation: Misc.

General Terms
Design, Human Factors, Experimentation; Measurement.

INTRODUCTION
Paper interfaces have the potential to integrate computing in schools more seamlessly than mice, keyboards, and screens. Paper is already omnipresent in schools. In general, paper has a lot of affordances that cannot be replaced by digital technologies [18]. For example, paper is freely annotated, easy to navigate, can be transported and duplicated easily, etc. In the case of geometry, paper is an essential ingredient to learning the use of fundamental tools like compass or protractors.

ITS'12, November 11–14, 2012, Cambridge, Massachusetts, USA.

Following the seminal work of Wellner [23], many authors have used paper interfaces to bridge the digital divide between a paper document and its electronic form. Paper is used to bridge the digital divide because it often embodies documents. What matters in this context is the content it carries. Yet paper is also a physical body which can be moved, rotated, and flipped. Paper can thus be used to implement Tangible User Interfaces (TUI) that integrate seamlessly into classroom environments, where paper is ubiquitous. This is especially true for practical reasons: as demonstrated by Costanza et al. [2], a paper-based TUI can be produced with basic tools, such as printers, scissors, and glue. Furthermore, paper-based interfaces have the same properties as flat objects, making them perfectly compatible with 2D geometry, the main part of the curriculum in primary schools.

This article focuses on the tangible nature of paper. We present Quads, an activity based on the manipulation of pieces of paper to learn the classification of quadrilaterals. A pilot study and an in-situ study in primary schools revealed that the very manipulation of the elements of the interface can be analysed to generate indicators about the learning process. We explain how the traces of the interaction can be used to measure the progress of the activity, hesitation when doing the activity, difficulty level of the activity, and how the work is divided among a group of pupils during the activity. Finally, we discuss how these indicators can be applied in different Technology Enhanced Learning approaches.

RELATED WORK
Traditional geometry education, based on regular paper, has a major shortcoming: only static figures can illustrate the concepts. However, Garcia et al. [9] claimed that students appreciate the ability to repeat and play a geometrical construction as allowed by a computer. Furthermore, Dynamic Geometry Software (DGS) such as Cabri Géomètre [13] and GeoGebra[1] enable learners to explore the dynamic behaviour of a geometrical construction, i.e. what is free to move and what remains fixed under given constraints. Straesser [22] explains how DGS opens new possibilities in geometry education by enabling geometric constructions not easily possible with pen and paper. However, the use of interfaces based on windows, icons, menus and pointers involves the risk of spending more time learning software than learning geometry [12], as these

[1] `www.geogebra.org`

interfaces are completely different from the typical geometry tools frequently used in classrooms such as a pen, ruler, or compass. Paper is a less distracting interface: Oviatt et al. [15] showed that the more interfaces mimic pen and paper (digital pen, graphic tablet), the less they induce an extraneous cognitive load.

There are several examples of digital pen and paper systems used for education. They are often based on Anoto technology, which consists of printing a microscopic pattern on paper which is detected by a camera embedded in a pen, such that the strokes can be acquired. For example, Pietrzak et al. [17] presented a system augmenting note taking in the classroom. They concluded from interviews with teachers that augmented paper could address the separation of digital content shown in the classroom, oral explanations, and notes. CoScribe [21] integrates pen-and-paper-based interaction techniques that enable users to collaboratively annotate, link, and tag both printed and digital documents. Other systems are commercially available.

Paper interfaces are not limited to interactions based on a digital pen. Books are a popular way to control Augmented Reality applications. For example, Martín-Gutiérrez [14] and his colleagues designed a book combined with a screen to develop spatial abilities among engineering students. They measured a positive impact on the spatial abilities, and the users found the system easy-to-use, attractive, and useful.

Paper interfaces can further rely on their tangible nature by using artefacts that are more important for their presence and position than for their content, such as gaming cards. Perlman [16] made programming in Logo accessible to children by ordering cards in rows, which represent commands in sequences. Do-Lenh et al. [7] used paper tokens to build a concept map on an augmented tabletop system.

The tangible and document nature of paper interfaces are not mutually exclusive. For example, Song et al. [20] used a paper cube and a digital pen to combine the advantages of physical and digital modelling tools in the early stages of architectural training. Zufferey [24] proposed an interface that combines tangible and paper elements to teach logistics. The mix of tangibles and paper is particularly powerful in education, where manipulation is often key to experimentation, and documents help make reflection become persistent.

To create paper interfaces, it is thus possible to use one of the several frameworks analysing TUI's (e.g. [8]). Particularly, Hornecker and Buur [10] broadened the scope of TUI to *tangible interaction*, by describing more than the *data-centred* view of TUI. They add the *expressive-movement-centred* and the *space-centred* views of tangible interaction. The former focuses more on the interaction itself than the physical-digital mapping. The latter focuses on the position of the user in space. This is interesting if we draw parallels in the pedagogical context. The *expressive-movement-centred* view of tangible interaction can be seen as a way for pupils to enact a concept to learn. For example, discovering angles can be done by rotating a piece of paper, or by making it follow a circular course. The *space-centred* deals with aspects like the division of labour, which can result naturally from the spatial disposition of tangible resources, which orient the roles of learners in a group, as shown by Jermann et al. [11].

This leads us to believe that studying the tangible interaction of a group brings useful insights about the learning activity. This is the field of research called Interaction Analysis [6]: it consists of automatically analysing a computer-mediated activity to produce indicators to be reused, to qualify, or to adapt the activity. These indicators are typically computed from the traces of an interaction between learners and computers via a mouse and keyboard. However, this is also possible with tangible interactions, and these indicators are even richer, because interaction happens in the real world.

This paper shows four indicators that can be drawn from the tangible interaction with a paper interface, which we present in the next section. Based on the positions of the pieces of paper (which are tracked by a camera), we can deduce which problem solving step the pupils are on, how much they hesitate in the activity, how much difficulty they have on an exercise, and how they distribute the roles within the group.

DESCRIPTION OF THE SYSTEM

Technology

Our system for geometry education is built on the TinkerLamp, a tabletop system developed at our laboratory [24]. The TinkerLamp, shown in Figure 1, incorporates a camera and a projector directed to the tabletop surface via a mirror. The augmented surface is of dimension 70 $\times$ 40 centimetres. The camera and projector are connected to an embedded computer, so that the interaction with the hardware is minimum for the end user: switch on or off. It only needs to be plugged into an electric outlet.

Figure 1: Our camera-projector system on a table, along with various types of objects which can be augmented: sheets, cards, tools and wooden blocks. In Quads, only sheets, cards and cardboard shapes are used.

The interface mainly consists of *sheets* and *cards* and cardboard *shapes*. The properties and behaviours of these interface elements are identified by the system using the fiducial markers printed on them. We use fiducial markers, which are similar to ARTags[2], to identify and precisely track the various elements of the interface. Since the interface is projected from the top, it is possible to use interface elements (paper sheets and cards) as a projection surface in addition to the tabletop surface. We refer to this kind of interface as a *scattered interface* [3], because it allows for interaction and distribution in space and among people. This characteristic is central to gather the indicators.

Description of the Activity

We designed the first activity as a pedagogical script to introduce the classification of quadrilaterals (squares, rhombuses, trapezoids, etc.) as shown in Figure 2. The script consists of *sheets*, four *cards*, and a set of quadrilateral cardboard *shapes*. We discuss the properties of each type of element in detail in another article [1]. Each of these elements has a fiducial marker to identify it and was produced with a regular printer. The cardboard shapes were numbered, so that they could be referenced with the sheets.

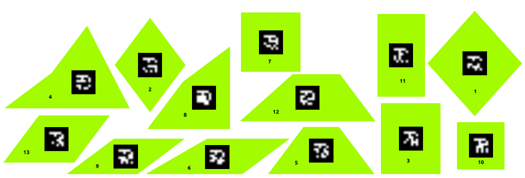


Figure 2: The numbered cardboard quadrilaterals used in the study.

The sheets, which include activity instructions, are shown in the left part of Figure 3. They consist of a short instructional text and two areas (marked with different colors - gray and white) denoting two different classes of quadrilaterals. For the last page, related to the classification of a square, a rhombus, and a rectangle, the two areas overlap because the square shares the properties of the two others. The text instructs the learner to use the three cards shown in Figure 4 to find a common characteristic in a subset of shapes, and separate them into two classes. The cards have a small text describing their function. When a specific card is brought close to a shape, the system will display the given characteristic of the shape (such as side length, angle measures, or parallel sides).

The learner is instructed to place a fourth card next to the current page once the shapes are placed in the classification areas (see the top right part of Figure 3). If all shapes have not been placed in the areas, the learner will be reminded to do so. If the grouping is not the expected one, the learner will be invited to try again. If the grouping into areas is correct, the formulation of the answer will appear, e.g. *"Good job! Quadrilaterals with a pair of parallel sides are called trapezoids"*. Feedback is intentionally trivial; the cards are not meant to replace teachers.

[2] `http://www.artag.net`

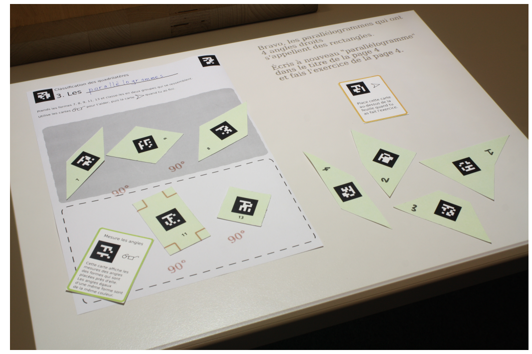


Figure 3: The components of Quads. (Left) Five cardboard quadrilaterals are classified into two groups on the instruction sheet; a card displays the measure of the angles of a rectangle. (Right) The feedback card displays the validation text.

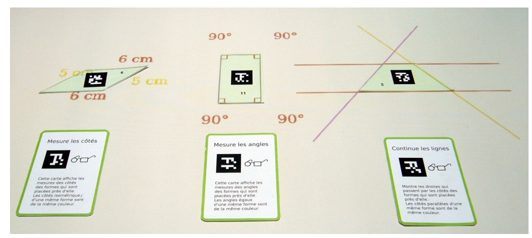


Figure 4: An example of the information displayed by each of the cards.

The seventh (last) page of the sheets is a recapitulation exercise that does not use the TinkerLamp. In the first part, the pupils have to write the names of the shapes under a figure representing them. In the second part, pupils have to link a list of quadrilateral names to a list of properties (four right angles, two pairs of parallel sides, one pair of parallel sides, four sides, and four equal sides).

Scenario

We illustrate the intended use of Quads with the following scenario. This scenario allows us to introduce three steps in the problem solving process, which will be revealed from the manipulation of the paper interface: *inferring*, *applying*, and *validating*. First, pupils have to *infer* a classification rule, i.e. make a hypothesis about the criteria that discriminates one set of shapes from another. Second, pupils can check their hypothesis quickly by *applying* the tool card related to the rule on the shapes. Third, if it fits, they can *validate* their classification rule by placing the shapes in one of the two areas of the exercise sheet and placing the validation card.

The scenario is as follows: Jim and Sarah are two sixth graders who are trying to learn the classification of quadrilaterals. They already know about most names and the appearance of quadrilaterals (square, rectangle, rhombus, parallelogram, trapezoid). They also know how to measure a side, and the meaning of perpendicular and parallel, but they do not know how to check these properties or measure angles.

They are given the leaflet of six exercise sheets, the 13 cardboard shapes, and the four cards. Jim reads the instructions of page 1 aloud and selects the corresponding cardboard shapes. Jim guesses (*infers*) that the shapes with equal sides belong together. Sarah reminds him to use the tool cards. She takes the tool card measuring sides and tries it on the shapes (*applies*). After Sarah places the shapes on the sheet, Jim takes the validation card for feedback (*validates*). He reads it aloud, and Sarah repeats the name of the category (rhombuses). The pair goes on through each exercise sheet, until they reach the final recapitulation one, and return to their respective desks to complete it.

PILOT STUDY

In this section, we report on the first deployment of this activity outside of the laboratory. A school agreed to host a demonstration of the system to its pupils. The demonstration occurred on a Friday afternoon, during the period of time normally allocated to homework. Three classes participated: two fifth grade classes and one sixth grade class; i.e. the pupils were 10 to 12 years old. The goal was to validate the design of the activity.

Ten groups of variable sizes (one individual, six groups of two, two groups of three, and one group of four) were given five minutes to go through the first page of Quads. They were given the sheet, the five cardboard shapes shown in Figure 5, and the three tool cards, but not the feedback card. They were simply asked to use the tool cards on the shapes and place the shapes into two groups. After five minutes, we asked them why they grouped the shapes in the way that they did. We then asked them to explain the purpose of each card.

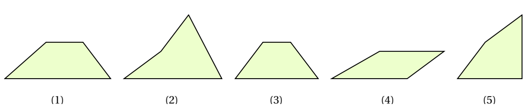


Figure 5: The five quadrilaterals used in the pilot study.

Supporting exploration

The classification expected by the design was the distinction between trapezoids (Shapes 1, 3, and 4 in Figure 5) and non-trapezoids (Shapes 2 and 5 in Figure 5), using the card that shows the lines passing along the sides of the quadrilaterals where parallel lines are coloured the same. Of course, any classification can be made as long as it comes with a justification.

The classifications produced are shown in Figure 6. We see that this activity supports exploration surprisingly well: five different classifications were produced and eight different justifications were given (the pupils could find the expected classification with a different justification). For example, a group used the fact that Shapes 2 and 5 can be assembled like a tangram, and that they both had five centimetre sides as classification criteria. Other groupings were geometrically sound. For example, shape 5 has a right angle, as opposed to 1, 2, 3, and 4, which do not.

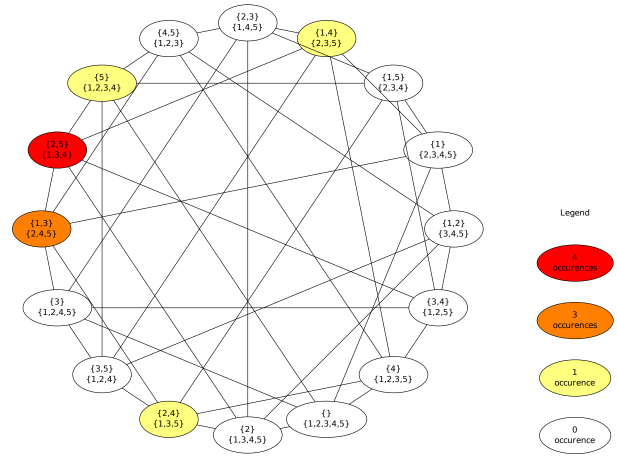


Figure 6: The classifications proposed by the pupils out of the 16 possible classifications. Each node represents one possible classification. Their colour indicates how often they were proposed by a group. Each classification is linked to the classifications that are possible after changing one element.

This five minute activity could have been followed by a rich discussion among the pupils, directed by a teacher. The augmentation contributed to the diversity of the answers: it is likely that pupils would have based their classifications on the appearance of the shapes rather than the characteristics revealed by the tool cards (e.g. the length of the sides). The artefacts produced by the augmentations, such as the line continuing the sides which formed a triangle, were also interesting from a pedagogical point of view: the teachers could explain the difference between the pertinent properties of a *figure* (e.g. the sides of a cube remain parallel in an isometric representation) and the artefact linked to the *drawing* (e.g. not all the sides of a cube have the same length in an isometric representation). This distinction is central in geometry education.

Observations

The interactions were based on the position of the paper elements: when a card was brought close to a shape, it would display additional information. There were two ways to do that: either move the shape towards the card, or move the card towards the shape. The latter seems more intuitive, as cards are usually kept in the hands. However, four groups out of ten moved the shapes towards the cards.

Within the groups moving the shapes rather than the cards, an interesting interaction emerged. Three groups created a test bench by placing all of the tool cards together, and bringing the cardboard shapes in the common neighbourhood of the cards to show all of the related information at once, as shown in Figure 7.

We also observed another emerging interaction pattern that addressed technical limitations of the system. Indeed, there was a perceptible lag (of a few hundred milliseconds) between a card being close to a shape, and the display of the

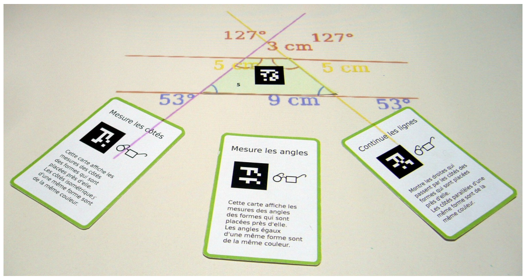


Figure 7: The single display of the cards shown in Figure 4 can be combined into a "test bench", where cardboard shapes are placed to display all of their characteristics at the same time.

related information. Moreover, the single marker on the cards and shapes was often occluded (e.g. by the hands of the pupils), preventing the detection of the elements of the interface, and thus the resulting display. To address this, some groups interacted in two steps: they would first manipulate the cards and shapes, and then leave the interface alone for the system to display the information. We suppose that this technical limitation can have a pedagogical value, and, for this reason, we decided not to 'fix' this limitation for the in-situ study. Indeed, the fact that the pupils stop their manipulation to wait for feedback might actually foster an observation time that could be beneficial for their reflection [4].

Finally, we observed that the size of the group had a strong impact on the course of the activity. On one extreme, the pupil manipulating the interface alone seemed very intimidated by our presence and did not dare interact too much. On the other extreme, the four pupil group was easily distracted and focused less on the task. Three pupils per group seemed like the best compromise.

IN-SITU STUDY

Figure 8: The physical set-up of the experiment: three pupils sitting under the TinkerLamp, in a spare room of their school.

We deployed the activity in another study, which took place in a spare room of another primary school (see Figure 8). The pupils came from two sixth grade classes (i.e. 11-12 year-old pupils). We could only extract pupils from workshop-like activities related to mathematics. As a consequence, our study was limited to two periods (of 45 minutes) per class. We decided to have the groups go through the whole activity, which meant that only one group per period could take part in the study. Two groups from each class tried the system during one period each, after a brief presentation to the whole class.

Based on the lessons drawn from the pilot study, we asked the teachers to form groups of three pupils. For each teacher, the first group was composed by higher performing students than the second group. Each group was asked to complete pages one to six with the TinkerLampand then complete page seven (the recapitulation exercise) individually on separate desks. The expected classifications for each of the pages are shown in Figure 9. We did not reserve time at the beginning of this study for the pupils to get familiar with the system, because in the pilot study, they immediately understood how to use the interface.

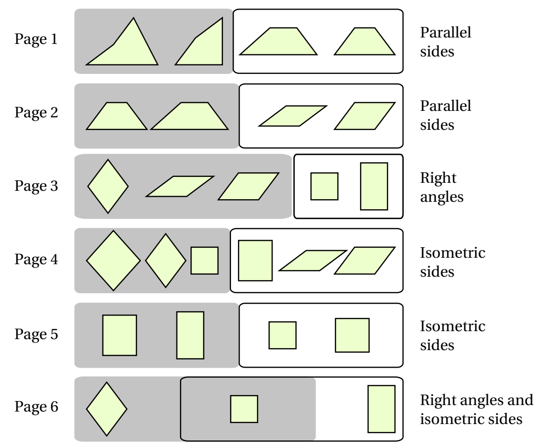


Figure 9: Expected classifications for the first six pages of the study. The criteria for each classification is shown on the right. The classification of page 6 is not a partition: a square is in both the rectangle and rhombus classes.

We provided the feedback card to the pupils, with a mechanism to make intensive trial and error strategies difficult: the feedback card had to be placed on the sheet, i.e. on top of the shapes, which prevents from moving them. The experimenter gave one exercise sheet and its related cardboard shapes to the group at a time, after the feedback card validated the classification for that particular exercise.

During the experiment, we recorded the position of the fiducial markers detected by each image captured by the TinkerLamp. This allowed us to replay the augmentations projected during the study. More importantly, it allowed us to trace the trajectory of each element of the paper interface. We also recorded a video of each group, but do not report on the analysis of the dialogues, since we focus on indicators that can be collected automatically.

We first analyze two simple measures of performance: a pre/post-test, and completion time. These measures will then be used as a reference to compare indicators computed from properties of the manipulation of the various elements of the paper interface: the presence of the various pieces of paper indicate which step of the problem solving process the pupils are in; the speed of the pieces of paper indicate how much the pupils hesitate; the vertical transitions indicate how much difficulty the pupils have on an exercise; and the horizontal transitions indicate how the pupils dispatch the roles among the group.

Performance

We used page 7 of the activity as a pre-test and post-test. The score was computed as the number of quadrilaterals that could be named correctly. For nine out of twelve pupils, the score did not change, mostly because of a ceiling effect: the answers were already correct in the pre-test. Three pupils improved their score from four to six, from two to four, and from three to four, respectively. These three pupils were in groups 3 and 4; groups 1 and 2 scored perfectly on both tests. The explanation lies more in the group formation than in the activity: groups 1 and 2 came from one class, while groups 3 and 4 came from another.

More importantly, the teacher purposely formed the groups of homogeneously performing pupils: pupils from groups 1 and 3 were higher performers than those from groups 2 and 4. This is reflected in the completion times: the time to solve the exercises (excluding exercise 4) was 515, 631, 819, and 911 seconds for groups 3, 1, 4, and 2, respectively. Exercise 4 was excluded from the calculation, because group 3 did not receive this exercise: the experimenter erroneously skipped the page.

All the groups managed to go through the activity in less than 40 minutes, which is important, because it fits the 45 minute periods between the two breaks. Figure 10 shows the time spent on each exercise, from the presentation of the page by the experimenter to the positive feedback given by the validation card.

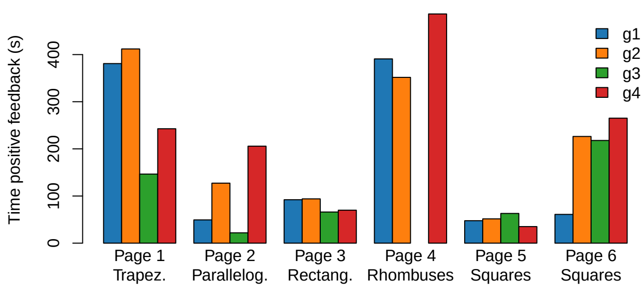


Figure 10: Time spent by each group on each activity.

Figure 10 highlights the differences between the exercises: pages 2, 3, and 5 were more obvious, since they could be completed on a perceptual basis (compare with Figure 9). This helped the pupils formulate a hypothesis very quickly, but they double-checked their hypothesis with the tool cards in most cases before viewing the feedback. Only one pupil tried to validate a classification immediately without using the tool cards.

Page 4 stands out in completion time. This is due to the fact that the appearance was misleading: the first intuition of the pupils was to group the square and the rectangle together because they have equal angles, but the expected classification was actually based on the length of the side. Pupils tried several hypotheses before correctly classifying the shapes. Page 1 also stands out, mostly because it was the first exercise: pupils were still discovering the activity and the interface of the system to solve it. Finally, page 6 was grouped with the more challenging exercises, because it was slightly different: the two areas of the page in which to classify the shapes were actually overlapping, and one shape (the square) was in the overlap of these two regions. We now present indicators that corroborate these explanations.

Use of the Augmentations as Problem Solving Step Indicator

The most basic information regarding the manipulation of an interface element is its use, i.e. whether it is activated or not. In the case of a tool card, it means that its functionality was being used by being close to a shape. Not all of the cards were useful for completing each exercise. For example, the card showing the lengths of the sides was useful to distinguish rectangles from squares, but not to distinguish squares from rhombuses. A mixed effect anova with the group as a random factor showed that the useful cards were used significantly more than the others ($F[1, 64] = 7.24$, $p < 0.01$). In general, it informs us that the pupils were not toying with the system, and understood which cards could help them. More particularly, it is a first indicator on the learning activity: by detecting which tool card is activated, it is possible to determine whether the pupils are trying to *infer* the expected classification, or whether they are still guessing.

The associations between the tool cards and the cardboard shapes can bring more information. Theoretically, this association is many-to-many: a card can display the attributes of several shapes at once, and a shape can have several of its attributes displayed. In practice, it is a one(-card)-to-many(-shapes) relationship: a card often displayed the attributes of several shapes at the same time, but a shape very rarely had several of its attributes displayed at the same time. Throughout the whole experiment, cards were associated to one shape 1.6 times more often than to multiple shapes, while shapes were associated to one card 10.5 times more often than to multiple cards. We assume that when a tool card is activated on one shape, the pupils are still trying to *infer* the rule. If the card is applied to multiple shapes, the pupils are more probably in the *applying* step, because they have grouped shapes together, and can compare the characteristics displayed by a card. Of course, it is easy to know when the pupils are in the *validating* step: the shapes are on top of the exercise sheet.

Average Speed as Hesitation Indicator

We kept a trace of the position of each piece of paper throughout the study. This allows us to recreate the trajectory of the various pieces of paper (see Figure 11). This is very rich information. To exploit it, we concatenated the trajectories of paper elements of the same type: shape, validation card, tool card, and sheet, for each exercise of each group. Dividing this cumulated length by the time each group spent on each exercise gives an average speed of a type of interface component.

This average speed is a quantity of movement performed by the pupils on the interface, normalized over the length of the exercise; it does not correspond to any actual speed.

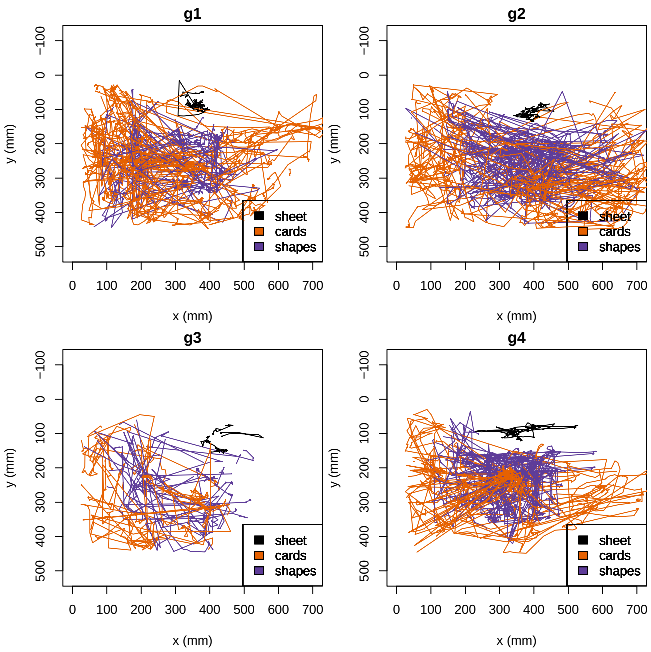


Figure 11: The traces of the various pieces of paper.

Figure 12 shows the average speeds of each kind of component. A mixed effect anova with the group as a random factor showed that each kind of component had a significantly different average speed from the others ($F[3, 84] = 32.40$, $p < 0.0001$). On average a sheet moved by 7 mm/s. It is the most stable element. The augmented area under the TinkerLamp, delimited by the projected white background, defines a virtual border for the exercise sheet, out of which it is hard to move. Anyway, moving the sheet away from the centre would mean excluding one of pupils who are sitting on the side. Second comes the validation card, at 18 mm/s, which is simply brought above the sheet when needed. Third come the tool cards, at 32 mm/s, which are manipulated more often. The most mobile element are the shapes, at 52 mm/s; they have to move between the areas of the exercise sheets and the neighbourhood of the tool cards.

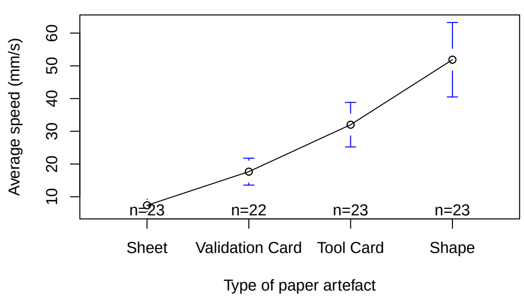


Figure 12: Average speeds of the different kinds of paper artefacts.

We now consider the average speed of the shapes, the most mobile interface element. More time-consuming pages (1, 4 and 6) see a decrease of this average speed. A mixed effect anova with the group as a random factor showed that this decrease is significant ($F[5, 14] = 8.34$, $p < 0.001$). The speed can thus be used as an indicator of the hesitation of the pupils: on trivial pages, they will obviously move the cardboard shapes more than on pages where they hesitate. This may be because the exercise is new, as with page 1, or because the exercise is harder, as with pages 4 and 6.

Verticality as Difficulty Indicator

We can refine the grain of our analysis by only observing the y-coordinate of the positions of the cardboard shapes relative to the y-coordinate of the position of the sheet. Indeed, the goal of the activity is to place shapes in one of two boxes which are on top of each other. Figure 13 shows an example of this data. It actually corresponds to the path taken by a group towards a solution. One way to formulate the exercise is the following: shapes are associated to a binary type for each sheet, and the goal is to place the ones of a same type within the boundary of areas that stretch over the whole width of a page. The problem is thus solved when all shapes of a given type are within the vertical range of an area.

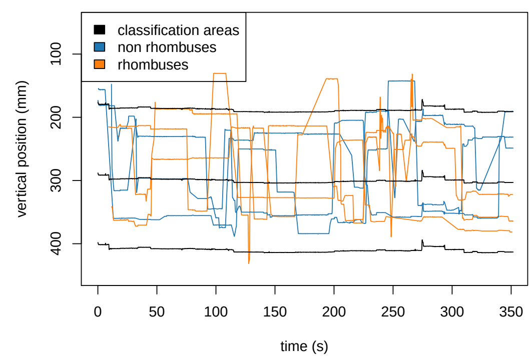


Figure 13: The y-coordinate of the position of the various elements of the paper interface as a function of time, for one group and one exercise. This allows us to visualize the position of the cardboard shapes (blue and orange, depending on the expected classification) relative to the areas on the exercise sheet (delimited in black).

We can then make the y-coordinate of a cardboard shape discrete by defining one value per classification area on the sheet (i.e. two values for the first five sheets, and three values for the sixth sheet, which has two areas and their overlap). What is interesting then is the number of transitions from one area to another, because it means that a shape was moved to another category. In other words, the more transitions that happen on the discrete vertical coordinate of a cardboard shape, the more changes have been made to a solution. The number of vertical transitions is thus an indicator of the amount of difficulty that the pupils are having. As seen in Figure 14, pages 4 and 6 stand out from the other pages. The finding here is that page 1 does not stand out. This means that the increased time needed for solving page 1, and the increased average speed of the paper elements previously found, are not related to the difficulty of the task. On the first page, pupils are beginning to discover the activity and the interface and do not yet know how to manipulate the interface elements. The fact that we did not reserve time for the children to familiarize themselves with the interface allowed us to make this distinction: pupils can spend more time on an exercise because they are having difficulties with the exercise (as indicated by the number of vertical transitions) or because they are hesitant about how to use the interface (as indicated by the lower speed of manipulation).

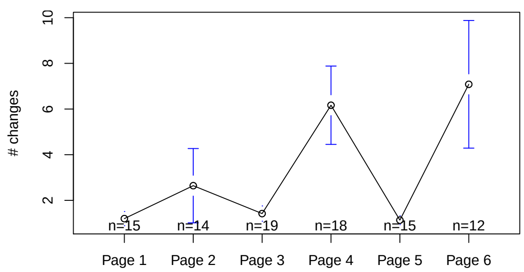


Figure 14: Number of vertical transitions per exercise sheet.

We fitted several models to explain the number of vertical transitions, and the best fit is a mixed effect model (the group being a random variable) with the difficulty of the exercise sheet being a factor ($F[1, 87] = 126.51$, $p < 0.0001$), the group performance level being a factor ($F[1, 2] = 43.92$, $p < 0.05$), and the interaction of the two of these factors ($F[1, 87] = 25.78$, $p < 0.0001$). This model is visualized in Figure 15. It categorizes the exercise sheets into two difficulty levels (reflected in Figure 14), and the groups into two performance levels (based on the group's composition by the teachers, corroborated by previous observations). We see that the number of vertical transitions significantly increases on difficult pages, and with lower performing groups. Furthermore, when these two conditions are met, the increase is even higher. The number of vertical transitions is thus a measure of the difficulties that a group of pupils faces on an exercise.

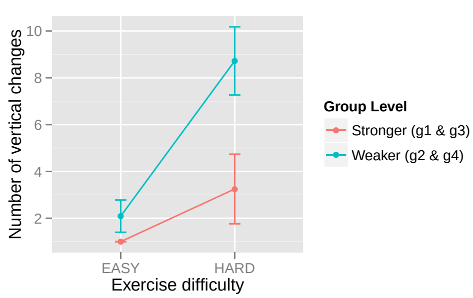
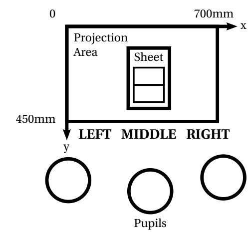


Figure 15: Number of vertical transitions per exercise sheet.

Horizontality as Division of Labour Indicator

Similar to the verticality of pieces of paper that we just investigated, we define the horizontality as the x-coordinate of the position of a piece of paper (card of shape) relative to the sheet. We show that it allows us to visualize the participation of each pupil. As shown in Figure 16, the three pupils sat next to each other. The exercise sheet was always in front of the MIDDLE pupil. The experimenter stood to the LEFT of the group, distributing the cardboard shapes from the LEFT of the group. The position of the pieces of paper was hence a hint at the balance of participation: the pupil on the RIGHT had to request or otherwise fetch the interface elements.

(a) Three pupils sitting in front of the augmented area, with the sheet in the middle.



(b) A schema of the positions of the pupils revealing the three areas defined by the position relative to the exercise sheet.

Figure 16: The positions of the pupils.

For example, Figure 17 shows the positions of the cardboard shapes and cards relative to the first exercise sheet. This allows us to observe the difference in collaboration between groups 2 and 4: the use of the cards was more balanced between the members of group 2. In both cases, the pupil on the RIGHT started far away from the pieces of paper. However, in group 2, the pupil on the RIGHT grabbed a cardboard shape after three minutes, and a card after 4 minutes, in order to do measurements. The pupil on the LEFT took them back, but the pupil on the RIGHT took the validation card, and used it twice, before the pupil on the LEFT took it back. In group 4, the pupil on the RIGHT was more shy and did not participate in the exercise.

First, observing the time spent by the pieces of paper in the three sections relatively to the position of the sheet (LEFT, MIDDLE, and RIGHT), we can see three kinds of collaboration types (see Figure 18). The collaboration of groups 1 and 2 happened naturally; it is unbalanced in favour of the LEFT pupil because the shapes and sheets were initially placed by the experimenter on the left side. Group 3 shows another kind of collaboration: the RIGHT pupil did not manipulate anything in her section. Instead, she was monitoring and leading the manipulations of the other members of the group. Finally, Group 4 was artificially balanced: the experimenter imposed a turn-taking rule for the pupils to manipulate, after realizing that the RIGHT pupil was not participating at all.

Similar to the vertical changes, we can define the horizontal transitions as the number of time a piece of paper changes sections (LEFT, MIDDLE, or RIGHT). This corresponds to a pupil exchanging (either by taking or giving) pieces of paper. This provides an important complement to the previous data, by indicating how much the pupils cooperate. This is different from the division of labour: if the pupils evenly dispatch the elements of the interface among them and work independently, there is an even distribution of labour, but no cooperation. Group 2 showed the other extreme: they exchanged the

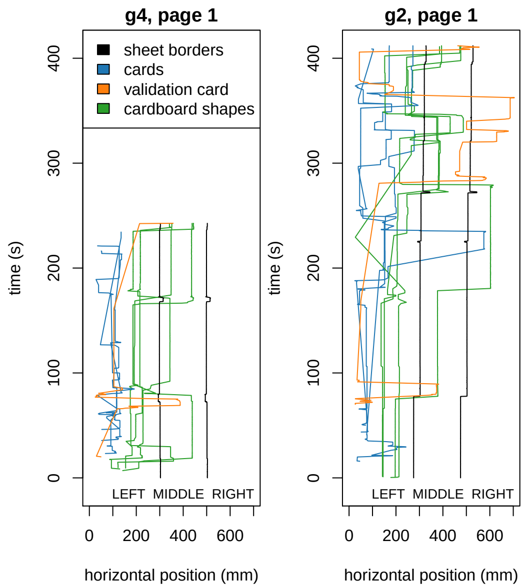


Figure 17: The x-coordinate of the position of the various elements of the paper interface as a function of time, rotated horizontally. This shows the position of the pieces of paper relative to the first exercise sheet (see Figure 16b)

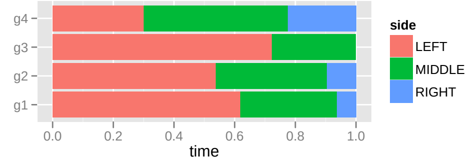


Figure 18: Time spent on each section of the collaboration surface by the pieces of paper.

pieces of interface about twice as much as the other groups. This is to contrast with Group 4, who had a more even repartition of the interface elements due to the intervention of the experimenter, but this did not significantly increase the cooperation. Note that a higher cooperation is not by itself a sign of a good collaboration. In the two higher performing groups, two pupils were manipulating, and one was overseeing, while the two other groups were less coordinated and worked more separately. Indicators can only be used after being interpreted, as we will discuss in the next section.

DISCUSSION

In summary, we found four indicators that could be extracted from the manipulation of the paper interface for Quads. These indicators are derived from the position of the various pieces of paper. First, the position of the tool cards relative to the cardboard shapes gives an indication about the problem solving step. Using the right tool card is a hint that the pupil is close to the solution, and applying it to multiple shapes indicates that the pupil has a hypothesis on how the quadrilaterals should be grouped. Second, the speed of the various elements of the interface shows how much the pupils hesitate. Increased hesitation was seen when doing the first page, when the activity was unknown, and when doing the more challenging pages. Third, a projection of the position of the cardboard shapes on the vertical axis of the exercise sheet indicated how much difficulty the pupils had in the construction of the solution, even if they did not request feedback. We showed that this was different from the time spent on or the hesitation when doing an exercise: the first exercise was trivial, i.e. the pupils did not have much difficulty, but they hesitated to use the interface because it was new to them. Fourth, the horizontal projection of the position of the pieces of paper was an indicator of the distribution of the roles among the groups of pupils.

These indicators are not automatically applicable, because they do not directly qualify the learning activity. For example, hesitation is a good thing if it corresponds to a reflection, but too much hesitation is not productive; too little hesitation is acceptable if it is the result of an exercise being too easy for a group, but not if it is the result of a lucky guess. Indicators are thus the basis of a retroactive loop on the learning group. The indicators need to be interpreted within their context, and this interpretation can be used to generate feedback on the group.

Many TEL approaches are based on this principle, explained in more detail by Soller et al. [19]. They show three families of systems that support the management of collaborative learning interaction, which differ in the exploitation of the indicators. In a mirroring tool, pupils are shown the indicators and left free to decide what to do with them. Meta-cognitive tools are similar, but also show a desired value for the indicators, so that the pupils aim at a desired state of interaction. Finally, guiding tools actually process the indicators and propose a remedial action for the pupils to reach a desired interaction state.

Orchestration [5], a more recent trend in Computer Supported Collaborative Learning, can also profit from the extractions of indicators from the manipulation. Orchestration refers to the tasks of teachers to identify and exploit learning opportunities and constraints in real time. This task is very challenging in a classroom: teachers have to integrate tight time constraints, expectations of the curriculum, practical matters (e.g. a forgotten book), the energy of the pupils, etc. A big part of this task consists of monitoring the class to acquire information. In this context, computing indicators from the manipulation of pupils on a tabletop can support the teacher in the orchestration task. It would even give a sense of activities based on paper without augmentation: the added value could be the tracking of the various pieces of paper, in order to provide indicators to the teacher in real time about the learning activity comparable to the one achieved if a teacher was monitoring only one group continuously.

CONCLUSION

We presented Quads, a pedagogical activity based on a paper interface utilizing augmented reality for pupils to explore the classification of quadrilaterals. In a preliminary study, we illustrated how Quads supported this exploration, and observed how pupils used the paper interface. In a following in-situ study, we investigated how the manipulation of a paper interface can be used to compute indicators on the learning activity. We compared these indicators to various performance data (tests, completion time, and evaluation of the groups from the teachers) to explain how they can be interpreted. We then discussed how these indicators can be applied as the input of a variety of TEL systems to manage the collaboration of pupils.

By observing how pupils manipulate a paper interface, we extracted some features that can be used as basic design guidelines. For example, cards are easily used as a function that can be applied to several objects. More importantly, the way Quads was designed allowed for easy extraction of the indicators we described. For example, the exercise sheets are laid out in a way that the y-coordinate of cardboard shapes maps directly to the solution state, and the changes of this value map to the difficulty. The workspace is set up in a way that the x-coordinate maps directly to the 'owner' of a piece of the interface, and the changes of this value show the coordination among the group. Finally, the tools are dispatched into independent pieces of paper, which allows us to know which function is being used and how, indicating where the group is on the path to a solution.

We do not claim that our interpretation of the indicators is perfect. Instead, our contribution is to inspire designers of TEL to use paper interfaces as a way to easily design activities that highlight targeted characteristics of a TEL activity. For example, the simple design of the exercise sheets supported the extraction of features related to the difficulty of and the collaboration in an activity. We hope that this approach will inspire other TEL researchers to tailor interfaces to help them investigate their own questions.

In future work, we believe that it would be possible to use further indicators from the manipulation of a paper interface. We could exploit the scattered aspect of paper interfaces to model the cognition of the pupils with a higher granularity, revealed by which element of the interface is being used, or how. Furthermore, there are many other features that can be exploited from the manipulation of a paper interface, such as the trajectory of the pieces, how they are stacked, how they can be combined, etc. This opens a wide range of possibilities as to the design of paper interfaces that makes indicators easily collectable.

ACKNOWLEDGMENTS

The authors wish to sincerely thank the teachers for their precious collaboration, as well as Olivier Guédat for building the TinkerLamp, and Chia-Jung Chan Fardel for her help with the second study.

REFERENCES

1. Bonnard, Q., Verma, H., Kaplan, F., and Dillenbourg, P. Paper interfaces for learning geometry. In *7th European Conference on Technology Enhanced Learning* (2012).
2. Costanza, E., Giaccone, M., Kueng, O., Shelley, S., and Huang, J. Tangible interfaces for download: initial observations from users' everyday environments. In *CHI '10* (2010).
3. Cuendet, S., Bonnard, Q., Kaplan, F., and Dillenbourg, P. Paper interface design for classroom orchestration. In *CHI '11* (2011).
4. Cuendet, S., Jermann, P., and Dillenbourg, P. Tangible interfaces: when physical-virtual coupling may be detrimental to learning. In *BCS '12 Proc. of the 25th BCS Interaction Specialist Group Conference* (2012).
5. Dillenbourg, P., and Jermann, P. Technology for classroom orchestration. *New Science of Learning: Cognition, Computers and Collaboration in Education* (2010).
6. Dimitrakopoulou, A., Bollen, L., Dimitriadis, Y., Harrer, A., Jermann, P., Kollias, V., Marcos, J. A., Martínez, A., and Petrou, A. State of the art of interaction analysis for metacognitive support & diagnosis, 2006.
7. Do-Lenh, S., Kaplan, F., and Dillenbourg, P. Paper-based concept map: the effects of tabletop on an expressive collaborative learning task. BCS-HCI '09 (2009).
8. Fishkin, K. P. A taxonomy for and analysis of tangible interfaces. *Personal and Ubiquitous Computing 8*, 5 (2004).
9. García, R. R., Quirós, J. S., Santos, R. G., González, S. M., and Fernanz, S. M. Interactive multimedia animation with macromedia flash in descriptive geometry teaching. *Computers & Education 49*, 3 (2007).
10. Hornecker, E., and Buur, J. Getting a grip on tangible interaction: a framework on physical space and social interaction. In *CHI '06* (2006).
11. Jermann, P., Zufferey, G., Schneider, B., Lucci, A., Lépine, S., and Dillenbourg, P. Physical space and division of labor around a tabletop tangible simulation. In *CSCL '09* (2009).
12. Kortenkamp, U., and Dohrmann, C. User interface design for dynamic geometry software. *Acta Didactica Napocensia 3* (2010).
13. Laborde, C., Keitel, and Ruthven, K. The computer as part of the learning environment: the case of geometry. In *Learning from computers:Mathematics education and technology*. Springer-Verlag, 1993.
14. Martin-Gutiérrez, J., Luis Saorin, J., Contero, M., A., M., Pérez-López, D. C., and Ortega, M. Design and validation of an augmented book for spatial abilities development in engineering students. *Computers & Graphics 34*, 1 (2010).
15. Oviatt, S., Arthur, A., and Cohen, J. Quiet interfaces that help students think. In *UIST '06* (2006).
16. Perlman, R. Using computer technology to provide a creative learning environment for preschool children. Tech. rep., M.I.T., 1976.
17. Pietrzak, T., Malacria, S., Tabard, A., and Lecolinet, E. What do u-note? an augmented note taking system for the classroom. In *PaperComp 2010: 1st International Workshop on Paper Computing. Workshop at Ubicomp 2010* (2010).
18. Sellen, A. J., and Harper, R. *The Myth of the Paperless Office*. MIT Press, Cambridge, MA, USA, 2003.
19. Soller, A., Martínez, A., Jermann, P., and Muehlenbrock, M. From mirroring to guiding: A review of state of the art technology for supporting collaborative learning. *International Journal of Artificial Intelligence in Education 15*, 4 (2005).
20. Song, H., Guimbretière, F., Ambrose, M., and Lostritto, C. CubeExplorer: an evaluation of interaction techniques in architectural education. In *INTERACT '07* (2007).
21. Steimle, J., Brdiczka, O., and Muhlhauser, M. CoScribe: integrating paper and digital documents for collaborative knowledge work. *IEEE Transactions on Learning Technologies 2* (2009).
22. Straesser, R. Cabri-géomètre: Does dynamic geometry software (DGS) change geometry and its teaching and learning? *International Journal of Computers for Mathematical Learning 6*, 3 (2002).
23. Wellner, P. Interacting with paper on the DigitalDesk. *Communications of the ACM 36*, 7 (1993).
24. Zufferey, G. *The Complementarity of Tangible and Paper Interfaces in Tabletop Environments for Collaborative Learning*. PhD thesis, 2010.