My Hands or my Mouse: Comparing a Tangible and Graphical User Interface using Eye-Tracking Data

Lorenzo Lucignano
lorenzo.lucignano@epfl.ch

Sébastien Cuendet
sebastien.cuendet@epfl.ch

Beat Schwendimann
beat.schwendimann@epfl.ch

Mina Shirvani Boroujeni
mina.shirvaniboroujeni@epfl.ch

Jessica Dehler
jessica.dehler@epfl.ch

Pierre Dillenbourg
pierre.dillenbourg@epfl.ch

CHILI - EPFL
Rolex Learning Center - Station 20
CH-1015 Lausanne - Switzerland

ABSTRACT

Tangible User Interfaces (TUIs) have drawn the interest of HCI and learning communities because of their potential positive impact on the learning experience.

In this paper, we describe a preliminary study of a TUI application for training spatial skills of carpenter apprentices. We designed a tangible interface to perform a CAD modelling activity in a way that resembles what apprentices do in the workspace: shaping a wooden brick through sequential cuts by using a saw. The core of the study is to compare the effects of TUI and GUI on the user experience, by taking advantage of eye-tracking data. We report two main findings: first, the successful employment of eye-gaze tool in TUI research which represents a novelty per-se. Second, a significant impact of the TUI on the user experience which gives some insights about the cognitive benefit of tangibles.

Categories and Subject Descriptors

H.5 [**Information Interfaces and Presentation**]: User Interfaces; K.3.1 [**Computer Uses in Education**]: Computer-assisted instruction

General Terms

Design, Human Factors

Keywords

Tangible Interfaces, Eye-Tracking, Vocational Training

Introduction

One main challenge in designing tools for technical and vocational education is to bring together abstract concepts, such as spatial thinking, and the daily workspace practice. Vocational students often perceive theoretical knowledge as irrelevant when it does not apply directly in their daily work practice [17]. Particularly for craftsmen, the physical contact with their creations is a fundamental feature of the job and it deeply influences their mathematical reasoning, that is often *framed by the context of the workshop and shaped by familiar tools* [14]. Our work focuses mainly on the use of tangible interfaces for training spatial skills. The development of spatial skills is part of the curricula of several professions, such as carpentry, engineering, and architecture, and its importance is well recognized in developing expertise in STEM domains [21]. Enhanced visualization skills are needed to read construction plans, to sketch 3D structures on paper or a tablet and to fully utilize tools such as Computer-Aided Design (CAD) software. Spatial skills can be trained and computer-based environments are promising alternatives to classic paper-and-pencil drawing lessons [19, 1]. We believe that TUIs are even more effective for spatial skill training compared to graphical UI (GUI), since the physicality of the tool can support the user in building a mental model of an object and can provide an intermediate level of abstraction between a real object and its representation on a screen [3].

We designed and developed an activity for training carpenters' spatial skills. The activity consists of a CAD task, during which the apprentice shapes a brick according to a given concrete model. In this study, we expose the design of our tangible tool and the comparison with a GUI implementation. We will primarily focus on the results obtained from eye tracking data, which provides insights into the impact of the physicality and concreteness of the interface on the user experience. The differences found in the gaze behaviors represent the main contribution of this study, as well as the employment of eye-tracker in TUIs research.

In the next sections we present: (1) a brief literature review on TUIs and eye gaze analysis; (2) a description of the experimental task, the setup and the terminology used in the results section as well as the research questions; (3) a summary of the results; (4) a discussion of the results and the conclusions.

FabLearn 2014 Stanford, CA USA

Related Work

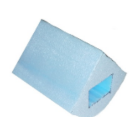
Tangible user interfaces can benefit learning for various reasons. Several studies have reported an increase of students' engagement when using tangibles (e.g. [16]). Interaction with tangible interfaces lowers the entry barrier and makes them more accessible to novices [22]. The physicality of TUIs supports behaviors such as gesturing and physical movement which require perception and hence support cognition and learning [7] . Moreover, TUIs may be particularly suitable for collaborative learning tasks compared to classical graphical interfaces, by providing a shared work-space and making it easier to see each other's actions [18]. Regarding spatial skill training, Kim et al. [12] studied the effect of TUIs compared to GUIs on designers' spatial cognition. The results showed that the manipulation of 3D physical objects improved the perception of spatial relations, and supported the exploration and discovery of different design solutions. Cuendet [2] proposed a tabletop TUI for training spatial visualization skills of Swiss carpentry apprentices. According to his study, even slight design changes may significantly affect effectiveness of the tools; For instance, manipulating a tangible with the same shape as the controlled virtual object improved learners' performances in comparison with a manipulative of a completely different shape [3]; Moreover, providing an immediate feedback of users' actions, could prevent them from reflecting on the learning task and hence negatively impact learning [4].
Despite all the previous research on TUIs, it is not still clear what features of tangibles may foster learning gains compared to the use of virtual materials [13]. Eye-tracking methodology has been rarely employed for exploring TUIs, although it has been highly promising in interaction and usability research [10]. Fitts, Jones and Milton [6] have employed eye-trackers to discover differences in the gaze patterns of pilots using two control systems for the aircraft. The percentage of dwells[1] on an instrument provided a ranking of the importance of tools on the control panel, whereas the percentage of transitions between the instruments described some tendencies for the subjects to check areas in a specific order, hence providing guidelines for the spatial arrangement of the elements of the interface. The average duration of a dwell is usually related to a difficulty in extracting information. Hendrickson [8] showed that the average dwell duration on a menu window increased with the number of items the user was asked to select. This result suggests that the dwell duration depends on the decision-making time. The relation between fixation duration and processing of the information was also addressed by Vlaskamp and Hooge [20], investigating the user search performances in a crowded scene. According to their study, the average fixation duration was increased by a high crowding level, probably due to an increase of the processing time for the elements under the gaze. In the context of Computer Supported Collaborative Learning (CSCL), joint attention in collaborative learning tasks has been explored through the use of dual eye-tracking. In [11], the authors used synchronized eye-trackers to evaluate the level of collaboration between two programmers working on a section of code. Results suggest a positive correlation between productivity and high joint visual recurrence.
Thus, the eye-gaze analysis has already been used in several HCI fields to investigate those dimensions, such as learner's cognitive effort or collaboration quality, that are extremely relevant to TUI research. Hence, we strongly believe it is worth to investigate the effectiveness of eye-tracker as a novel research tool in TUI studies. Particularly, in our experiment, through exploiting the eye-tracker data, we hope to shed new light on the differences of the gaze behavior when using a tangible or a graphical interface.

[1]A dwell is a lumped sequence of fixations on the same object or area.

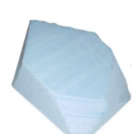
Experimental Setup

Research Question. Manipulating a mental model of a 3D object, as well as linking such a model to a virtual representation can be challenging. Hence our hypothesis is that having a tangible object resembling the virtual one can support spatial reasoning activities [3].
However, what happens when the physical object becomes increasingly different from its virtual representation during the task, passing from a state of "literal" correspondence to a "symbolic" one? If the tangible object and the virtual representation are not co-located[2], it might be that after a while the user forgets the physical properties of the tangible object, leading to a "tokenization" (e.g using it as a mouse). Our questions are: is there any advantage in using TUIs when the physical-virtual correspondence changes during the task? Do tangibles bring any benefits compared to a mouse-based implementation? In order to answer these questions, we will look for variations of gaze patterns between two experimental conditions, *tangible* and *virtual*.

The cutting activity. The cutting activity has been designed to teach the fundamentals of CAD software through a practice familiar to carpenters, such as cutting an object with a saw. This activity was conceived to be the first stage of a whole process which mimics the carpentry fabrication workflow: from the design of a object up to the final concrete realization of the object through computer numerical control machine (CNC) or traditional manual tools.
In the beginning of the activity, the participant received a styrofoam model that (s)he had to cut (Fig. 2). The corresponding starting shape was a rectangular-cuboid brick displayed on a screen (Fig. 1a). The virtual brick lay on a grid, whose concrete counterpart was a paper workspace taped on the table in front of the user. The brick could be moved on the grid and rotated only along the vertical axis. The saw was depicted on the screen as a cutting plane, which could be moved on the grid and tilted. Moreover, when in horizontal position, it was also possible to change its elevation from the ground.



(a) Trial 1

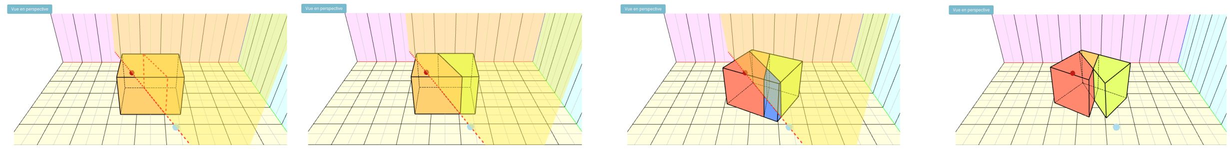


(b) Trial 2

Figure 2: Styrofoam Models

The cutting activity proceeded through a sequence of intersections between the plane and the brick: when the user decided to cut, the cutting plane split the brick into two or more fragments (Fig. 1b). Each fragment could then be selected and deleted; otherwise, it was possible to

[2]In the same location and close spatial proximity.



(a) Set the intersection (b) Perform the first cut (c) Perform the second cut (d) Remove fragment

Figure 1: Example of task sequence

perform several consecutive cuts to achieve more complex shapes (Fig. 1c and 1d). All actions were reversible[3].

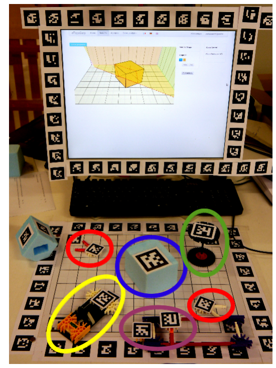
Design and Materials. There were two experimental conditions: *tangible* and *virtual*. In the tangible condition, participants used a styrofoam brick to manipulate the virtual object on the screen and several physical tools to control the cutting plane and to trigger the cut. The tangibles could be freely arranged or removed from the workspace area. In the virtual condition, all the tools were shown on the screen as graphical elements and they were controlled with a mouse. In both condition the target shape was provided as a styrofoam object.

The activity was implemented as a web application based on HTML5 standards and JavaScript. The system used a webcam to detect the objects and tools identified by one or more fiducial markers, that allowed getting their positions and orientations relative to the workspace. Fig. 3a shows the tangible implementation of the activity. The styrofoam brick in the blue circle was used to control the model on screen. In the beginning of the task, the control brick and its virtual representation had the same shape and dimension; However as the task progressed and the user performed several cuts and removed fragments from the virtual brick, the correspondence became less and less literal. The elements in red circles defined the position of the cutting plane. The wheel in the green circle tilted the plane between -90 and 90 degrees. When the plane reached the horizontal position, the slider highlighted in violet allowed changing the plane elevation. Finally, the tool in yellow acted as a utility knife and triggered the cuts (detailed view in Fig. 3b) .

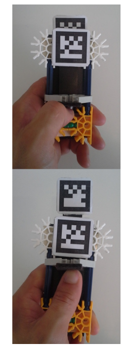
In the virtual condition, the tools were replaced with their graphical counterparts on the screen and are controlled by mouse (Fig. 3c). The user dragged and dropped the brick on the workspace and rotated it through a knob interface (the blue circles). The two markers defining the plane position were replaced by the two spheres in red circles, which were draggable as well. The knob in green and the slider in violet replaced respectively the wheel for tilting and the slider for changing the elevation. The utility knife had been replaced by a button.

The only graphical elements shared between the two implementation were a set of colored buttons to select the fragments, a text field containing the current tilt angle of the plane, and two buttons to delete a fragment and to undo the last action (Fig. 3c fuchsia squares).

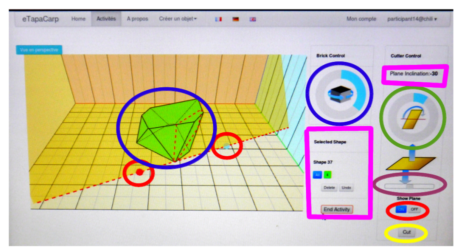
Participants. Sixteen undergraduate male students took part in the experiment, from 2nd to 4th academic year,



(a) Tangible Setup



(b) Utility Knife



(c) Virtual Setup

Figure 3: The two interfaces. Same color corresponds same function in both implementations.

7 Mechanical and 11 Microtechnique engineers. They had prior knowledge of 3D modeling and CAD software through their academical programs. Each participant was randomly assigned to one of the two experimental conditions.

Procedure. First, the participant filled out a questionnaire about age, gender, academic background, skill level in using CAD software, hours per week spent in using CAD, habit of playing 3D videogames and hours per week spent playing. Additionally, we asked them to indicate the titles of CAD software and videogames they were familiar with.

After the questionnaire, each student performed a pre-test to evaluate spatial visualization skills. The pre-test included a *mental rotation* test including 12 questions [15], followed by a *paper folding* test with 10 questions [5]. The time limit for each test was 3 minutes. At the next stage, the participant started using the interface. This stage included 3 parts: (1) the demo, in which the researchers explained the task through a demo session in order to get acquainted with the system. When the participant indicated to be ready, they started the next trial; (2) trial 1, the target shape was sym-

[3] A short video of the cutting activity can be found at: http://chili.epfl.ch/page-92256-en.html

metrical (Fig. 2a). The minimum number of cuts was 6 cuts, producing 10 fragments; (3) trial 2, the target shape was asymmetrical, which made it the more difficult trial (Fig. 2b). The minimum number of cuts to achieve this shape was 5 cuts, producing 5 fragments. During this phase, the participant wore SMI mobile eye-tracking glasses 1[4]. At the end of the task, a short interview about the experience was conducted.

Results

Two sources of data were used to analyse and compare users' experiences in the two experimental conditions: (1) application logs including user's action information and (2) eye-tracker data including the sequence of gaze fixation and their features (fixation start and end time, duration, position). These gaze events have been exported from SMI BeGaze software, which took care of processing the raw gaze data. The statistical tests were run separately on both trials, using ANOVAs or, whenever this was not possible, employing non-parametric tests. Repetitions were taken into account using mixed effect models when needed[5].
In the next sections we will use the abbreviation "ScreenOBJ" to indicate the virtual object displayed on the left part of the screen and the area around it. "ScreenGUI" refers to the right part of the screen containing the graphical interfaces. In the tangible setup it contains only the buttons to select the fragments and delete them, the undo button and a label showing the current tilt angle of the plane. In the virtual setup, this area contains also all the graphical control elements to rotate the brick, change the elevation of the plane etc., as mentioned previously.
The term "Brick" will be used to denote the styrofoam control brick available only in the tangible setup, whereas the term "Shape" will refer to the target styrofoam objects. The "Brick", the "Shape" and the "ScreenOBJ" form the set of the representation areas of interest (AOIs), since they embed spatial information of the object the participants are working on. The term "Workspace" will refer to the paper workspace and identifies an area of interest only for the tangible condition, since in the virtual condition the user had no brick and no tool on the grid[6]. Finally, we define an "Out" area which refers to everything not covered by the other AOIs. This area contained the mouse and sometimes the tangible tools not in use.
These six terms and the relative AOIs will be referred mostly in the eye tracking results (Fig. 4).

Pretest Scores. On average, participants got an score of 77.60% (SD: 23.11%) in mental rotation test and 86.87% (SD: 27.74%) in paper folding test. Compared to a recent study [2] in which the same material was used for evaluating spatial skills of carpentry apprentices , the performance level of our population was significantly higher ($t[453]=3.33$, $p<.001$ for the mental rotation test, and $t[453]=2.93$, $p<.01$ for the paper folding test). Carpenters on average scored 58.1% in mental rotation test and 66.4% in paper folding test.

[4]http://eyetracking-glasses.com/
[5]These cases will be conveniently introduced to the reader.
[6]Nevertheless, the paper workspace was also present in the virtual condition.

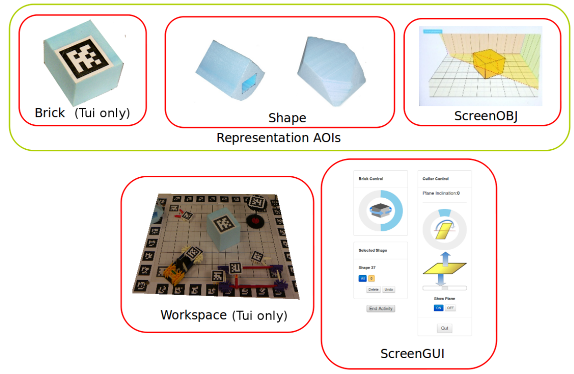


Figure 4: Areas of interest

Quality of Outcomes and Time Performance. The quality of the solutions the participants came up with has been assessed by asking five raters to give a score between 1 and 4: (1) the shape is completely different from the model; (2) one major mistake, but the target shape is still recognized; (3) shape is mostly correct, really minor mistakes ; (4) correct shape. The inter-rater reliability was 0.93. We did not find any relevant differences in the quality of the final solution between the two conditions as shown in table 1: in general, the solutions for trial 1 were mostly correct with an average score above 3, while for trial 2 the average score was 2.6.
The time to accomplish the tasks was slightly higher for the tangible conditions, in which participants took around two extra minutes compared to the virtual setup in both trials, as shown in Table 2. However, the difference was not significant (for trial 1 $F[1,14]=2.48, p=.13$, for trial 2 $F[1,14]=1.08, p=.31$).
By including time before the first cut for trial 1, the one-way test reveled that participants in the tangible condition performed the first cut earlier compared to the ones in the virtual condition. In particular, the first cut was performed on average after 51 seconds (SD: 13 s) using the TUI, whereas it happened after 1 minute and 6 seconds (SD: 14 s) using the mouse, and the difference was statistically significant ($F[1,14]=4.33, p=.05$). However, for trial 2 the time difference was not significant.

Table 1: Average Quality Scores

	Trial 1	Trial 2
Tangible	3.05 (*SD* 0.63)	2.65 (*SD* 0.52)
Virtual	3.08 (*SD* 0.83)	2.67 (*SD* 1.16)

Table 2: Average Duration

	Trial 1	Trial 2
Tangible	8 min and 16 s (*SD* 3 min and 8 s)	9 min and 42 s (*SD* 3 min)
Virtual	6 min and 7 s (*SD* 2 min and 10 s)	8 min an 6 s (*SD* 3 min and 8 s)

Fragments Created. When using the tangible and virtual interface, the participants respectively performed on average 10.5 cuts and 8.75 cuts for trial 1, and 7.37 cuts and 6,75 cuts for trial 2, however the difference was not significant: for trial 1 F[1,14]=2.54, p=.13, for trial 2 F[1,14]=0.36, p=.55. Surprisingly, we found a significant difference between the two conditions in terms of number of fragments created during the tasks: as shown in Fig. 5, the group using tangible interface created on average +67% fragments compared to the virtual condition in trial 1, and +46% in trial 2 (for trial 1 one-way *Welch's* F[1,9.26]=7.13,p=.02, for trial 2 F[1,14]=5.03,p=.04).

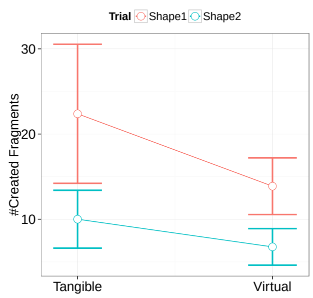


Figure 5: Number of fragments created

Gaze Analysis. Since the experiment duration varied among the participants, we conducted further analyses on the dwells in terms of percentages.

Fig. 6 shows the overall partition of the dwells on each AOI for the two trials. The first result is the sum of the average dwells spent on the "ScreenGUI" and "Workspace" using TUI is nearly equal to the average dwells spent on the "ScreenGUI" using GUI in both trials. Since these areas contains most of the control tools, this result has positive implications for the design of the interface (for trial 1 F[1,14]=0.21, p=.64, for trial 2 F[1,14]=0.27, p=.61).

The average percentage of dwells on the tangible brick constitutes a non-negligible amount in both trials. By restricting the analysis only to the representation AOIs, it is evident that the average percentages of "ScreenOBJ" are not statistically different between the two condition in both trials: for trial 1, tangible avg=72.32 (SD 10.30), virtual avg=72.43 (SD: 17.41); for trial 2, tangible avg=59.93 (SD 10.83), virtual avg=57.10 (SD 20.31). As a consequence, we can state that the transfer to the "Brick" is from the "Shape". Moreover, Table 3 shows that TUI users allocate less time to "Shape" compared to GUI participants and such difference is close to be significant in both trials(for Trial 1 *Welch's* F[1,8.74]=4.64,p=.06, for Trial 2 F[1,14]=4.24,p=0.05).

Table 3: Percentage of dwells spent on the "Shape" over the total dwells spent on representation AOIs

	Tangible	Virtual
Trial 1	13.47 (*SD* 6.19)	27.56 (*SD* 17.41)
Trial 2	27.17 (*SD* 7.12)	42.89 (*SD* 20.38)

In order to explore differences in the average duration of dwells between conditions, we employed linear mixed models. Given the nature of the test, the user identifier was taken into account as grouping factor.

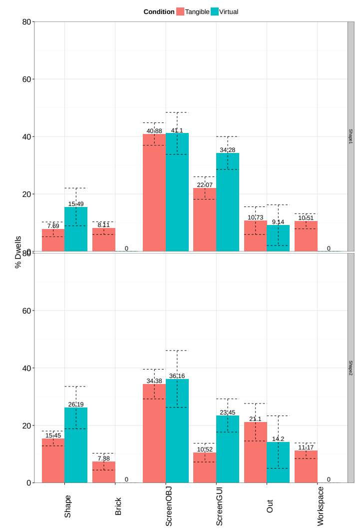


Figure 6: Proportions of dwells on the AOIs

In general, the results indicate that participants in tangible condition had on average shorter dwells towards the "Shape" area compared to virtual ones in both the trials. For trial 1, tangible users on average spent 616 ms on the "Shape" area (*Est.* = 616.09, *Std.E.* = 90.29, *t(291)* = 6.82, $p <$ .01), whereas in the virtual condition there was on average additional 250 ms, although the difference is close to be significant (*Est.* = 250.18, *Std.E.* = 128.39, *t(14)*=1.94, *p*=.07). For trial 2, the results are significant and indicate that participants in tangible condition spent on average 530 ms on the area(*Est.* = 530.57, *Std.E.* = 120.04, *t(855)* = 4.41, $p <$ .01), whereas in the virtual condition there was on average a plus of 420 ms(*Est.* = 420.21, *Std.E.* = 171.08, *t(14)* = 2.45, p = .02).

Comparing the average duration of the dwell on the "ScreenOBJ", we noticed an increase in the average duration of this area when using the virtual interface. The results from the linear mixed model analysis suggest that in trial 1 tangible users looked at the AOI on average 1.5 s (*Est.* = 1590.65, *Std.E.* = 100.71, *t(1408)* = 15.79, $p <$ .00). This average increases by 420 ms in the virtual condition (*Est.* = 420.12, *Std.E.* = 163.72, *t(14)* = 2.56, p = .02). The same trend is visible for trial 2, but less significant. In this case, the average duration for tangible users is almost 1.5 s (*Est.* = 1499.37, *Std.E.* = 108.19, *t(1662)* = 13.85, $p <$ .00), but the increment using the graphical interface is only 291 ms ((*Est.* = 291.92, *Std.E.* = 167.25, *t(14)* = 1.74, p = .10).

An overview of the transitions among AOIs is shown in Fig. 7 and Fig. 8. On each direct edge is reported the average percentage of transitions between the two areas over the total transitions. As expected, the transitions between "ScreenOBJ" and "ScreenGUI" characterize the virtual condition, since all the tools lie on the screen. As well, these transitions play an important role also in tangible condition during the trial 1, as shown in Fig. 7b. As for the percentage of dwells, in trial 1 (Fig. 7) the transitions between "ScreenOBJ" and "Shape" of virtual condition are split almost equally among the three representation AOIs in the tangible setup. The same effect does not emerge so clearly in trial 2 (Fig. 8), where the transitions from/to the "Brick" are less prevalent, mainly due to the "Out" area, which absorbs most of them. Table 5a and Table 5b show the average percentages of transitions between the representation AOIs for the tangible setup. In both cases, we noticed a ScreenOBJ centric distribution, which for trial 1 exhibits an equal distribution of transitions between Brick - ScreenOBJ and Shape - ScreenOBJ. However in trial 2, the transitions toward the Brick account only for the 25,36% (Sd: 13.70%), which is still an interesting proportion, but definitely smaller than the one toward the Shape (62,04% sd: 18.54%). Finally, the transitions between "Brick" and "Shape" amount to only a small percentage of the total transitions in both trial 1 and trial 2, respectively 10.42% (sd: 9.67%) and 12.59% (sd: 9.48%).

Table 4: Adjacency matrix of transitions among representation AOIs in Tangible Condition

	Shape	Brick	ScreenOBJ
Shape	.	5.72 (sd: 4.37)	21.49 (sd: 6.18)
Brick	4.7 (sd: 5.71)	.	19.72 (sd: 8.65)
ScreenOBJ	22.7 (sd: 6.59)	25.67 (sd: 7.69)	.

(a) Trial 1

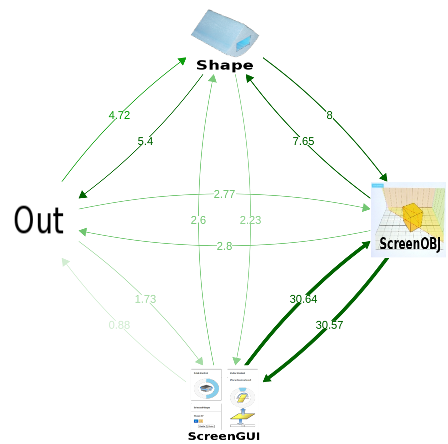
	Shape	Brick	ScreenOBJ
Shape	.	6.41 (sd: 5.72)	26.38 (sd: 10)
Brick	6.18 (sd: 5.88)	.	12.47 (sd: 7.84)
ScreenOBJ	35.67 (sd: 12.03)	12.89 (sd: 6.11)	.

(b) Trial 2

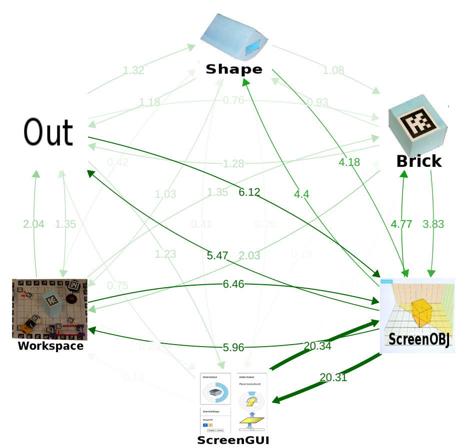
Results from the Interviews. Fifteen participants (out of 16) stated that shape 1 was easier than shape 2. Symmetry and proportions of the edge sizes in the first shape made it easier to figure out how to set up the cutting tool, in contrast with the irregular silhouette of the second shape which entangled finding a solution. Only one participant stated that he did not have to follow any rigorous geometric criteria for shape 2 (as any solution could be quite good) and hence it was easier.
The main strategy to perform the cuts was to keep the plane fixed on the workspace, set the inclination and then move the brick inside. It was adopted by 13 out of 16 participants, while only two participants kept the brick fixed and moved the plane. Two explanations for the fix-plane strategy were given: it was a legacy from the use of CAD software (e.g. Catia) and it was easier and more precise to move one object (brick) instead of two (markers of the plane).

In the tangible condition, the concreteness of the brick facilitated the interpretation of its virtual representation. The majority of participants in this condition stated that they rotated the brick to get a better perception of the depth on the screen. However, 7 participants (6 in the tangible condition) declared to prefer to perform the delete actions at the end although it seemed more natural to remove unwanted fragments after performing a cut. According to them, this was the easiest way to retain the correspondence between the control brick and the object on the screen.

Overall, participants gave a positive feedback for the tangible interface ("easy and/or fun"). One user also said that this tool could be helpful to teach CAD principles to his nephew. The virtual interface on the other hand seemed too "unusual" with those control knobs and the lack of more powerful functions. According to one participant, "it was really difficult to follow the wheel for inclining the plane while looking at the intersection".



(a) Transitions in the Virtual Condition

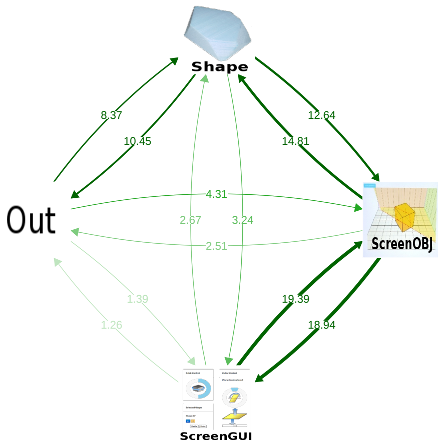


(b) Transitions in Tangible Condition

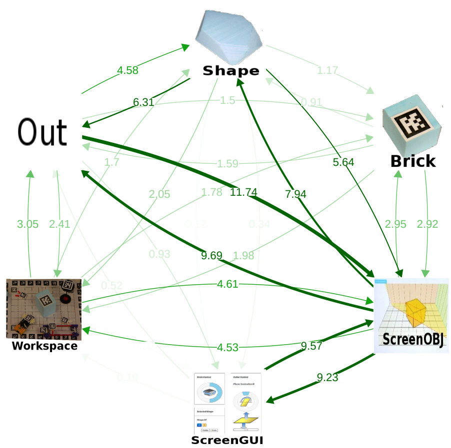
Figure 7: Transitions for Trial 1

Discussion and Conclusions

The aim of this study was to explore the impact of a tangible interface compared to graphical interface when performing a task which involves a change of the coupling between a physical representation and a virtual one over time.
The fact that the average percentages of dwells on the "Workspace", "ScreenGUI" and "Out" AOIs do not exhibit a significant difference between the two conditions may be an indicator about the homogeneity of the two interfaces, in the sense that there is no considerable overhead or penalty in the adoption of either the tangible control tools (i.e. wheel for the tilt angle) or their virtual counterparts. From the point of view of TUI design, these results indicate that a tangible interface can be effective as well as intuitive and engaging.
In the tangible condition, a significantly higher number of fragments was created by participants. Given that the av-



(a) Transitions in the Virtual Condition,



(b) Transitions in Tangible Condition

Figure 8: Transitions for Trial 2

erage number of cuts did not differ in both conditions, this result probably derives from the tendency of users to keep most of the fragments till the end. As reported in the interviews, this strategy allowed participants to keep a reference between the physical brick and its virtual representation on the screen, which otherwise would have been lost. However, another explanation could be a tendency to minimize the switching among the tools, preferring the use of one tool during longer periods instead of switching between the brick, the plane, the mouse etc.

The physical feedback provided by the brick seems to provide a positive effect on building a mental representation of the shape and the task: the shorter time before the first cut using TUI may indicate a more readily comprehension of the model and its 3D representation. The similar time until the first cut in trial 2 is probably due to a learning effect. However another explanation could be the novelty effect of the TUIs, that was lost in the second trial.

Although the literal correspondence between the physical control brick and the graphical model gets increasingly lost with each cut, the eye-gaze data shows a considerable percentage of transitions and dwells toward the control brick, indicating that participants kept on looking at such an area. The hypothesis that the tangible brick becomes a ”token” was not confirmed. This suggests that the participants continued perceiving the tangible object and its physical properties.

Moreover, there are significant differences in the gaze behavior on the ”Shape” and ”ScreenOBJ”, which is surprising since the contents of the two areas were the same in both conditions. The average duration of the dwell on the ”ScreenOBJ” was lower using TUIs, despite the average percentage of dwells being the same in both conditions. Longer duration is typically related to a difficulty in extracting information, thus this result suggests that the physical brick can help in understanding the graphical model. Indeed, our interpretation is that it is more difficult to extract information from 3D objects without the support of a physical object, which contains information that eyes and hands can easily perceive, such as the depth. On a screen, depth is obtained using dashed lines, which involves the additional cognitive step of decoding the order of surfaces and lines from their rendering properties.

The lower percentage of dwells on the ”Shape” in the virtual condition compared to the TUI condition does not necessarily mean that participants looked less at the area, but it indicates a split of the attentions between these two areas. ”Shape” represents the final goal, so it embeds all the information required to achieve the task, however the tangible representation acts as a control and embeds the digital information in physical form, which maximizes the coupling between manipulation and the underlying computation, reducing the abstraction between the physical action and the virtual action on the screen [9]. The direct alignment between the physical world system in which the shape is located and the virtual one could reduce the mental effort: the ”Brick” can provide a bridge between these two spaces, since it is located in the real world and, at the same time, on screen. Thus, what the user perceives in the physical world is also presented in the virtual one. Moreover, we believe that the longer average dwell duration on the ”Shape” in the virtual condition indicates difficulties with coding the execution plan directly in the graphical interface rather than difficulties with reasoning about the shape per-se. The simple action of positioning the 3D object in the virtual condition required a sequence of clicks or drag-and-drop actions, forcing the user to perform an extra mental effort, whereas manipulating the tangible brick was immediate and direct.

The graph plots illustrates the centrality of the ”ScreenOBJ” and its strong connection with the ”ScreenGUI”. Besides their relative proximity, the small size of the color palette for distinguishing the fragments of the block may have played a big role in increasing their connectivity: when there were more than ten fragments, the pigeonhole principle forced the users to a ”trail-and-error” behavior, which increased the percentages of transitions.

Regarding the representation AOIs, the transitions between ”Brick” and ”Shape” in TUI were quite rare: this result could be explained by the fact that the two areas represent diametrically opposed stages of the task, the initial state and the final one. Hence, the major transitions involve always the ”ScreenOBJ”: the Brick-ScreenOBJ references are needed especially to visualize the effect of the plane intersection after the positioning of the TUIs, and the Shape-ScreenOBJ transitions accounts for the actions of matching and planning.

Our study is preliminary in nature and focused on comparing TUI and GUI. The study was conducted in a laboratory setting with a relative small number of participants. Besides some technical issues, all final solutions were mostly correct, which led to a ceiling effect, since all participants were skilled in CAD software and modelling.

In conclusion, two main results came out of this study: first, eye trackers can be used as a research tool to capture variations among participants using TUIs. Its implementation in TUI research represents a novelty and we believe that this result contributes to its adoption as research tool to study the cognitive effects of tangibles, particularly, in order to facilitate the design of "hands-on" learning activities. Second, during the experimental task, the participants in the tangible condition have shown gaze values which can be interpreted as indicators of less demanding effort, suggesting some cognitive advantages in using TUIs even when the tangible object and its virtual representation do not share the same geometrical information. For a follow-up study, we plan to implement longer TUI activities in real carpentry classroom with larger numbers of participants with a wider range of spatial abilities. An extended version of the activity could include actually cutting the physical control brick after simulating the cut. This would give us the opportunity to validate our preliminary findings on a larger population in authentic classroom settings and to assess whether our TUIs are effective to facilitate spatial ability development.

Acknowledgements

We would like to thank Kshitij Sharma, for his help with the eye tracking analysis.

1. REFERENCES

[1] Contero, M., Naya, F., Company, P., Saorin, J., and Conesa, J. Improving visualization skills in engineering education. *Computer Graphics and Applications, IEEE 25*, 5 (Sept 2005).

[2] Cuendet, S. *Tangible Interfaces for Learning: Training Spatial Skills in Vocational Classrooms*. PhD thesis, EPFL, 2013.

[3] Cuendet, S., Bumbacher, E., and Dillenbourg, P. Tangible vs. virtual representations: when tangibles benefit the training of spatial skills. In *NordiCHI '12 Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design* (2012).

[4] Cuendet, S., Jermann, P., and Dillenbourg, P. Tangible interfaces: when physical-virtual coupling may be detrimental to learning. In *Proceedings of the 26th Annual BCS Interaction Specialist Group Conference on People and Computers* (2012), British Computer Society.

[5] Ekstrom, R. B., and French, J. W. *Manual for kit of factor referenced cognitive tests*. 1976.

[6] Fitts, P. M., Jones, R. E., and Milton, J. L. Eye movements of aircraft pilots during instrument-landing approaches. *Ergonomics: Psychological mechanisms and models in ergonomics 3* (2005).

[7] Goldin-Meadow, S. *Hearing gesture: How our hands help us think*. Harvard University Press, 2005.

[8] Hendrickson, J. J. Performance, preference, and visual scan patterns on a menu-based system: implications for interface design. *ACM SIGCHI Bulletin 20*, SI (1989).

[9] Ishii, H. Tangible bits: beyond pixels. In *Proceedings of the 2nd international conference on Tangible and embedded interaction* (2008), ACM.

[10] Jacob, R. J., and Karn, K. S. Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. *Mind 2*, 3 (2003).

[11] Jermann, P., and Nüssli, M.-A. Effects of sharing text selections on gaze cross-recurrence and interaction quality in a pair programming task. In *Proceedings of the ACM 2012 conference on Computer Supported Cooperative Work* (2012), ACM.

[12] Kim, M. J., and Maher, M. L. The impact of tangible user interfaces on spatial cognition during collaborative design. *Design Studies 29*, 3 (2008).

[13] Marshall, P. Do tangible interfaces enhance learning? In *Proceedings of the 1st international conference on Tangible and embedded interaction* (2007), ACM.

[14] Millroy, W. L. An ethnographic study of the mathematical ideas of a group of carpenters. *Learning and individual differences 3*, 1 (1991).

[15] Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., and Richardson, C. A redrawn vandenberg and kuse mental rotations test-different versions and factors that affect performance. *Brain and cognition 28*, 1 (1995).

[16] Price, S., Rogers, Y., Scaife, M., Stanton, D., and Neale, H. Using 'tangibles' to promote novel forms of playful learning. *Interacting with computers 15*, 2 (2003).

[17] Schaap, H., Baartman, L., and de Bruijn, E. Students' learning processes during school-based learning and workplace learning in vocational education: a review. *Vocations and Learning 5*, 2 (2012).

[18] Schneider, B., Jermann, P., Zufferey, G., and Dillenbourg, P. Benefits of a tangible interface for collaborative learning and interaction. *Learning Technologies, IEEE Transactions on 4*, 3 (2011).

[19] Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., and Newcombe, N. S. The malleability of spatial skills: A meta-analysis of training studies. *Psychological bulletin 139*, 2 (2013).

[20] Vlaskamp, B. N., and Hooge, I. T. Crowding degrades saccadic search performance. *Vision Research 46*, 3 (2006).

[21] Wai, J., Lubinski, D., and Benbow, C. P. Spatial ability for stem domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology 101*, 4 (2009).

[22] Zuckerman, O., Arida, S., and Resnick, M. Extending tangible interfaces for education: digital montessori-inspired manipulatives. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (2005), ACM.