Tangible vs. Virtual Representations: when Tangibles Benefit the Training of Spatial Skills

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ABSTRACT

Tangible user interfaces (TUIs) have been the focus of much attention in the HCI and learning communities because of their many potential benefits for learning. However, there have recently been debates about whether TUIs can actually increase learning outcomes and if so, under which conditions. In this article, we investigate the effect of object representation (physical vs. virtual) on learning in the domain of spatial skills. We ran a comparative study with 46 participants to measure the effects of the object representation on the ability to establish a link between 2D and 3D representations of an object. The participants were split into two conditions: in the first one, the 3D representation of the object was virtual; in the second one, it was tangible. Findings show that in both conditions the TUI led to a significant improvement of the spatial skills. The learning outcomes were not different between the two conditions, but the performance during the activities was significantly higher when using the tangible representation as opposed to the virtual one, and even more so in for difficult cases.

Author Keywords

spatial skills, spatial ability, learning, learning environment, carpenter

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: Miscellaneous

General Terms

Human Factors; Experimentation

INTRODUCTION

The interface of a technology is key to the use that people make of it. Designers and researchers are continuously striving to design interfaces that are more usable and efficient for the users' purposes. In the last decade, tangible user interfaces (TUIs) have become the focus of much attention in both the learning and the HCI communities because of the new possibilities that they open up. TUIs were first introduced as Graspable Interfaces [3] and then as Tangible Bits [6] with the idea of coupling the atoms of the physical world and the bits of the virtual world.

There are various reasons why TUIs could benefit learning. Several studies have reported an increase of students' engagement when using tangibles (e.g [14]). Tangibles can also lower the entry barrier to entry for novices [21]. They can promote collaborative learning by making it easier to see others' actions, to share a space of interaction, and to allow each learner to actively take part in the learning activities. Another advantage of tangibles is that they can provide external representations of a problem or an object. Working with multiple representations plays a key role in problem solving and learning [1, 8] by helping the learner to make inferences, find invariants, and gather information in a different fashion from each of the representations.

Figure 1. The Tinkerlamp

The physicality of tangibles also has potential benefits for

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learning. Assuming that perception and cognition are linked (see e.g. [12]), behaviors such as gesturing, physical movement and embodiment [5, 11] can benefit learning. As manipulating physical objects is assumed to be natural and familiar, using tangibles may also limit the cognitive effort dedicated to manipulating the system to allow the learners to focus on the core of their task. Physicality can also be beneficial for specific tasks, as mentioned by Marshall [9]: "three-dimensional forms might be perceived and understood more readily through haptic and proprioceptive perception of tangible representations than through visual representation alone".

However, most of those possible benefits for learning remain to be demonstrated empirically [9]. In this article, we study the impact of the physicality of tangibles on the training of spatial reasoning skills. We focus on the affordance of the tangible representation of an object by comparing it to the virtual representation of the same object. For this purpose, we conducted a study in which 46 participants used a TUI to solve exercises that required them to make a link between the 3D and 2D representations of an object.

We sought to examine the impact of a tangible representation (as opposed to a virtual one) on the behavior of participants and on their learning outcomes. The results show that while the type of representation does not have a significant impact on the learning gain, the use of tangible representations have a significantly positive impact on the performance during the learning activities, especially when the difficulty of the task increases. We discuss the implications of this finding for the development of future tangible learning environment.

RELATED WORK

Spatial skills

Spatial skills have been a significant area of research in educational technology since at least the 1920s [17]. While spatial skills are not a school subject per se, several works have shown that they are an important factor of students' interest and success in science, technology, engineering and mathematics (e.g. [20]). After having been controversial for a long time, it now seems that spatial skills are trainable, but that the long-lasting effect of such a training as well as how the acquired skills transfer from one domain to another remain open questions (see e.g. [18] for a recent overview). Training spatial skills can be done through eye-to-hand coordination activities, such as playing with construction toys at a young age, attending classes of drafting or mechanics, or playing 3-dimensional computer games. For example, Sorby [17] designed a special course for developing spatial skills that was based both on drawing and on multimedia activities. During more than a decade, she has systematically trained first year engineering students with weak spatial skills. On a shorter period of time, she then also trained middle school and high school students, showing that in all three cases, the training consistently and positively impacted the students performance on spatial reasoning problems.

TUIs and spatial skills

TUIs were first introduced as Graspable Interfaces [3] and then as Tangible Bits [6]. The motivation behind TUIs was to connect the physical world with the digital one by using physical artifacts. As mentioned in the introduction, there are many reasons why tangibles may benefit learning. The works linking TUIs and spatial skills are few and far between. Kim and Maher studied the impact of TUIs on designers' spatial cognition [7]. Comparing the usage of a GUI and a TUI, they showed that designers using the TUI recognized more spatial relationships, were more immersed in the task, and discovered new visuo-spatial features when revisiting their design. They concluded that TUIs demonstrated potential to support creative processes. In another comparison of a GUI and a TUI, the TUI allowed users with low spatial cognition ability to be less challenged by spatial problems [15]. Cognitive Cubes [16] is a TUI that was developed to allow the assessment of spatial and constructional abilities. Users of this system must use cubes that can be connected together to match a 3D shape that is displayed on a screen. Empirical studies showed that the results of the assessment done with Cognitive Cubes were comparable to those done with a traditional paper-and-pencil 3D assessment.

Those works have shown that spatial skills are trainable and that TUIs could be effective to develop them. This work builds upon those earlier findings and aims at studying TUIs as a direct means to train spatial skills. In particular this article explores the impact of having a real and tangible representation of the 3D object used in 2D-3D mapping exercises.

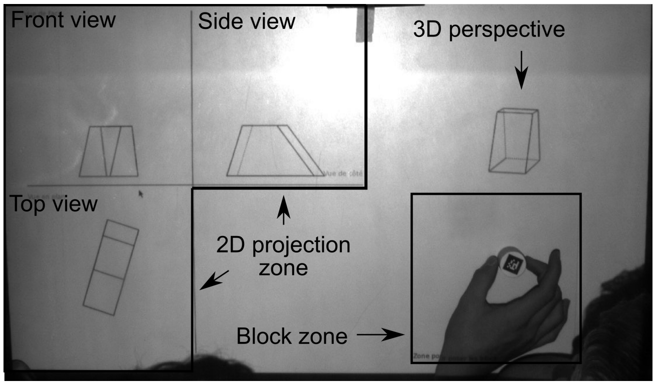


Figure 2. The tabletop display, shown for the token condition. The 2D projection zone contains the top, front, and side view of the object. The object is placed in the block zone, on the bottom right and, because this is the token condition, a 3D perspective of the object is shown.

EXPERIMENT AND METHOD

Technical setup

For this experiment, we used the Tinkerlamp, shown in Figure 1. The Tinkerlamp is a tabletop environment. It is composed of a camera and a projector directed at a tabletop via a mirror. The projection area, i.e. the playground for applications, is of dimension 70 by 55 centimeters. The lamp is able to detect tagged objects placed under it thanks to a tag tracking library similar to ARTag [10] and can provide visual feedback through the projector.

User interface

The tabletop display that students used is shown in Figure 2. It consists of two parts. The "Block zone" (gray square on the

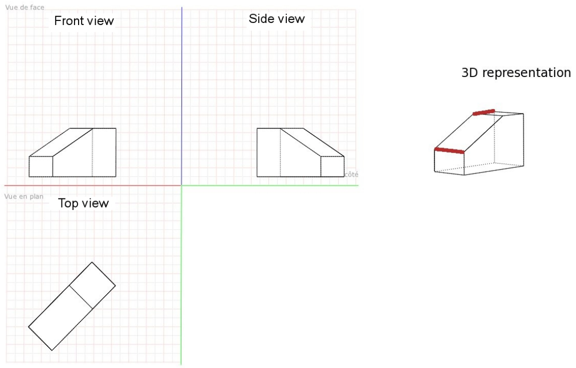


Figure 3. An example of the task: two edges are highlighted on the 3D representation, and the plan, face, and side views are shown. The task is to find the two edges on each of the three orthographic projections.

bottom right) is where the tangible objects are manipulated. The "2D projection zone" (on the left) contains three orthographic projections of the block: its top view (bottom left), its front view (top left), and its side view (top right). The object can be translated horizontally and rotated around the vertical axis and its movements are linked to the virtual representations projected on the tabletop. Instructions and feedback appear as pop-up windows.

Participants

The participants to the study were teenagers (mostly around 16 years old) enrolled in a 3-year dual carpentry training program, all studying in the same school. Carpenters must have excellent spatial skills, because they are required to establish a link between the 2D plan produced by the architect and the 3D structure that they build. In their training, they currently develop their spatial skills by performing drawing exercises in the domain of descriptive geometry. The exercises typically involve working with the 3 basic orthographic projections with a drawn 3D representation of an object – or vice versa. As shown in Figure 3, each of the 3 orthographic projections is a 2D plane projection of the 3D object from a different view: the top view, the front view, and the side view.

A total of 46 male apprentices in the first year of their training took part in the experiment. They had had little exposure to orthographic projections prior to the experiment. The apprentices were grouped by pairs. We chose to organize the apprentices in groups for ecological reasons, as they work in pairs most of the time at school. Each pair was randomly assigned to one of two conditions (see subsection "Conditions" below). In total, 13 pairs completed the experiment in the block condition and 10 in the token condition. Although it could be a potential future area of research, this experiment did not focus on the group dynamics.

Task

The experimental task was to identify and select edges from the orthographic projections that had been highlighted on the perspective 3D projection. There were either two or three edges highlighted on the object. When two edges were superposed, a right click selected the edge in the background whereas a left click selected the front edge. When an edge was not superposed with anything else, either the left or the right click could be used to select it. The orientation and the position of the virtual object could be modified by manipulating a tangible object.

The task was designed with the teacher to fit in the school curriculum. Learning to relate 2D projections of an object with its 3D one is the cornerstone of many of the activities of a professional carpenter and is trained mainly by performing drawing activities. The task designed for this experiment is close to the ones done in the regular curriculum and the learning outcomes were expected to be the same, although we did not test that empirically.

In total, the participants completed 13 of those exercises. The first one was an introductory exercise completed with the assistance of the experimenter and was not scored. Apprentices were then asked to complete 3 series of 4 exercises each, without any outside help.

Conditions

There were two conditions: the *token* condition and the *block* one. Figure 4 shows the same object being represented in both conditions.

In the token condition, the tangible object given to the participants to manipulate the virtual object was a small round token. In addition to the 3 orthographic projections, a 3D perspective view of the object was shown above the "Block zone". The highlighted edges were shown in another color on the 3D representation, as shown on Figure 3.

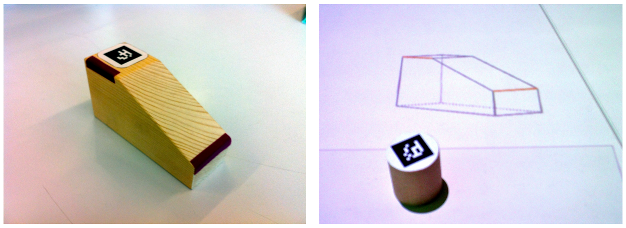
In the block condition, the small round token was replaced by the actual 3D object (the same shape that was shown on the virtual representations). Only the 3 orthographic projections were shown virtually, not the virtual 3D representation of the object, since the users had a tangible representation of the actual object.

The only difference between the two conditions was that of the visualization of the 3D representation of the object: in one case, it was virtual (token) while in the other it was tangible (block). This is key to the experiment since we want to study the impact of a tangible representation as opposed to a virtual representation. To this end the token was introduced so that on one hand, the mode of interaction – and especially the ease of manipulation that comes with a tangible interface – would be similar in both conditions; on the other hand, since the token has no resemblance with the actual model, its tangibility offers no benefit for the purpose of visualization.

Environment and method

The experiment was conducted during a drawing class, in a classroom in which two Tinkerlamps were set up in the back. The apprentices came in pairs to one of the Tinkerlamps to participate in the experiment. The experiment was conducted over 12 days with four classes.

The apprentices passed tests before and after completing the activity (pre-test and post-test). Both tests were done with paper and pencil and were designed for this experiment with the teacher. They were based on similar exercises of the school



(a) Block (b) Token

Figure 4. An object represented in both conditions: block (left) and token (right). In the token condition, the 3D representation is projected on the tabletop, and a token serves as a manipulation handle. In the block condition, the blocks serves both for manipulation and representation purposes.

curriculum. The pre-test contained 3 questions for a total of 12 points and the post-test contained 4 questions for a total of 14 points. All questions were identical in their form: the 3 orthographic projections of an object were shown, but not its 3D representation. An edge was highligthed on one orthographic projection, and the task was to find the highlighted edge in the two other projections. For each question, a number of edges were highlighted on one view (possibly on different views for different edges). Each edge correctly highlighted on one projection was worth one point, giving a maximum of two points per edge.

Statistical testing

The statistical tests were made using ANOVAs on linear models. Repetitions were taken into account using mixed effect models when needed.

RESULTS

The results compare the performance of the two conditions along several dimensions. We first look at the learning gain, computed as the difference between the pre-test and post-test performances, and at the task performance. We then go deeper into the analysis of the behavior to explain where the differences observed in the learning gain and task performance came from.

Learning gain

There was an overall improvement between the pre-test and the post-test in both conditions: the average score went from 51.6% in the pre-test to 72.4% in the post-test (+20.8% absolute gain, t(58)=6.89, $p<0.05$). The improvement was significant for both conditions, although participants in the block condition improved slightly more (+22.8%) than participants in the token condition (+18.3%) ($p>0.05$). Neither the relative learning gain nor the difference between the Z-scores of the pre-test and post-test were statistically significant between the two conditions. However, the general trend was that participants in the block condition had an overall higher improvement between the two tests, as shown in Figure 5. This is also confirmed by the large amplitude of the effect size (0.69) between the two conditions.

Learning performance during the treatment

Although there was no statistically significant difference between the two conditions in the test scores, there was one in the performance during the activities. One way to observe this is to look at the number of correct answers given by pairs of participants over the 12 activities. An answer to one activity is considered correct if all the edges to be found on each of the 3 views were found correctly. As shown in Figure 6, the apprentices in the block condition completed on average more activities correctly (10.3 vs. 8.2, $p<0.05$, F[1,21]=7.5)). Another way to compare the performances during the activity is to look at the percentages of correctly chosen edges, also in questions that have not been correctly answered as a whole. Apprentices in the block condition had a higher ratio of correct edges than apprentices in the token condition ($p<0.05$, F[1,21]=11.1).

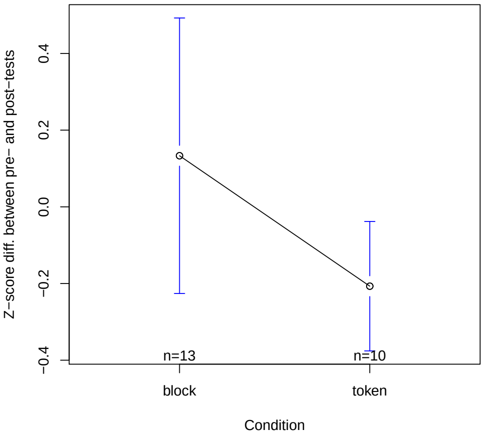


Figure 5. Difference between the pre-test and post-test Z-score by pairs of participants. The score of a pair was computed as the mean of its two members.

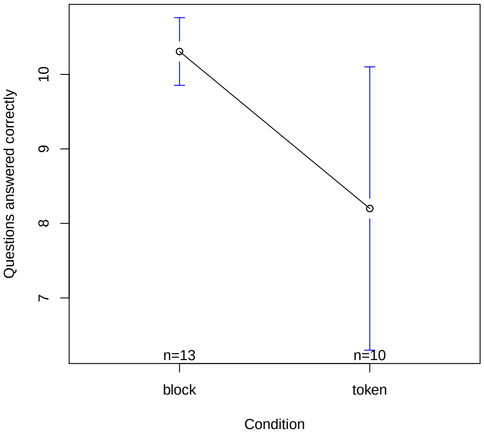
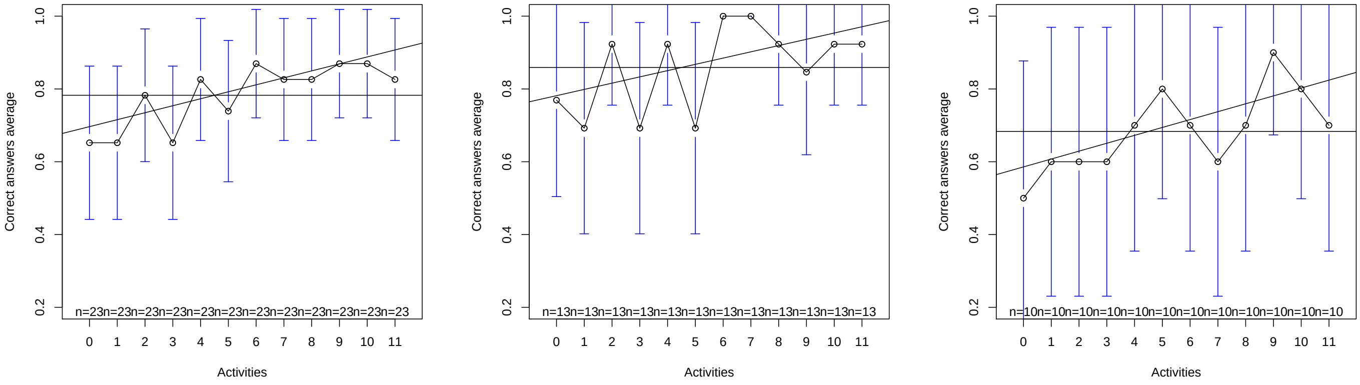


Figure 6. Number of treatment activities completed correctly by condition.

Performance improvement during the treatment

There was a steady progression over time while completing the activities, as shown on Figure 7a ($p<0.01$,



(a) All (b) Block (c) Token

Figure 7. Percentage of the average number of correct answers given during the treatment, together with the mean (horizontal line) and the line fit by means of linear regression, for all the participants (a), for participants in the block condition only (b), and for participants in the token condition (c). The activities are sorted by order of appearance, so as to represent the evolution of the performance over time.

F[1,252]=7.99). When splitting the participants by condition, the progression was only significant for those in the block condition ($p<0.05$, F[1,142]=4.6) and not for the token condition ($p>0.05$, F[1,109]=3.7). However, as can be seen in Figures 7b and 7c, the progression over the activities was comparable for both conditions. A slight ceiling effect may also be observed on Figure 7a and later on Figure 9. On the first one, one can see that the lowest score is about 0.8, which means that on average 80% of the pairs answered correctly to a question. The average ratio of correct edges per block type shown on Figure 9 confirms this, since even for the block with the lowest score, 9 edges out of 10 were found correctly.

The performance is directly linked to the number of mistakes: the fewer mistakes, the higher the performance. Since the performance improved with time, the number of mistakes must have gone down and looking at the evolution of the mistakes per view can inform us on the students' improvement. The only combination of view and condition for which the number of mistakes went down significantly is the side view in the block condition ($p<0.05$, F[1,142]<5.1). There is a similar trend for the side view in the token condition, although it does not reach statistical significance ($p<0.10$, F[1,109]=3.17).

	top	front	side
pre-test	0.63	0.53	0.41
post-test	0.78	0.71	0.67
gain	0.40	0.38	0.44

Table 1. Ratio of questions answered correctly, classified by the view on which the edge was involved. The relative gain is computed according to Equation 1.

The specificity of the side view

As explained in the previous section, there were performance differences between the two conditions. Analysing the performance by view gives more insight as to where the performance differences came from.

	Token			Block		
	top	front	side	top	front	side
pre	0.64	0.53	0.41	0.61	0.53	0.41
post	0.66	0.69	0.66	0.80	0.73	0.70
gain	0.06	0.34	0.42	0.49	0.43	0.49

Table 2. Ratio of questions answered correctly for the pre-test and the post-test, with the detail by condition. The relative gain is computed according to Equation 1.

In the pre-test and post-test

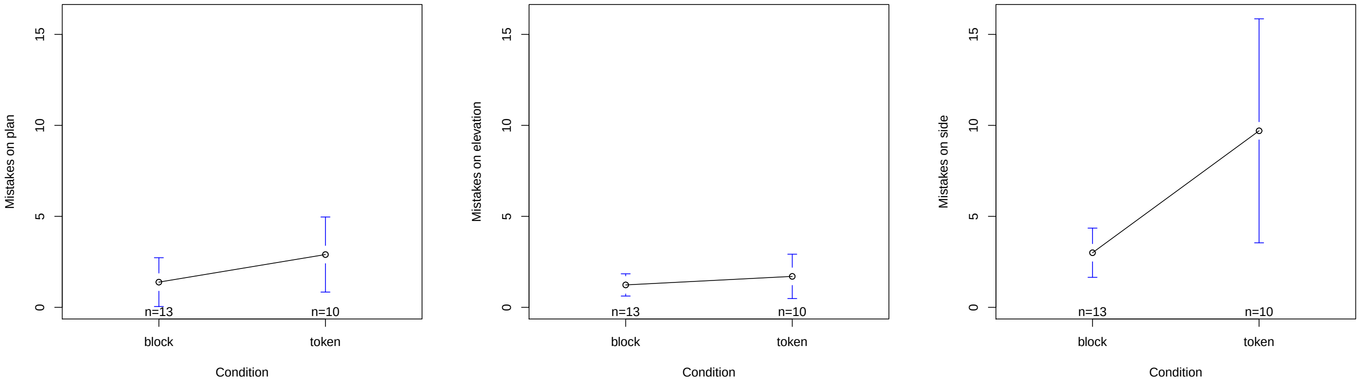
Each edge marked in the 3D model had to be found on each of the 3 views. Intuitively, and in agreement with previous work on mental rotation (e.g. [4, 13]), the side view should be the hardest one since it requires performing a 90 degree rotation. Indeed, the ratio of correct answers for the pre-test and the post-test is the smallest for the side view, as shown in Table 1. The same table shows that results were better on the plan view than on the front view.

Interestingly, the highest relative gain (Equation 1) between the two tests was made on the side view in both conditions. This is the case even when controlling for the higher possible improvement due to the intial low score on the side view. Table 2 shows that all instances of view and condition improved. The smallest improvement was the one of the token condition on the plan view. For each of the three views, the improvement in the block condition was higher than those in the token condition.

$$rel.\ gain = \frac{score_{post} - score_{pre}}{1.00 - score_{pre}} \tag{1}$$

During the treatment

Similarly to the test results, an analysis of the activities shows that the side view provided different results than the plan and the front view. Figures 8 shows the number of mistakes made on average by the groups in each condition. Only for the side view is the number of mistakes significantly different



(a) Plan (b) Elevation (c) Side

Figure 8. Comparison of the average number of mistakes made on each of the 3 views during the treatment activities per group. One mistake corresponds to an edge that has been wrongly selected or to an edge that has not been selected when it should have been.

between the two conditions ($p<0.05$, F[1,21]=7.34). Indeed, participants in the token condition made on average 9.7 mistakes on the side view, whereas participants in the block condition only made on average 3 mistakes on the same view.

Number of trials

The number of selections and unselections indicates the number of self-corrections performed by the participants, and can be interpreted as the difficulty that participants had to find the correct answers.

Per condition

Based on the ratio of the correct answers given during the treatment, it seems that it was harder to complete the activities with the token than with the block. The number of edges selected and unselected throughout the activities confirms that. The minimum number of selections for each view corresponds to the number of edges to find. Since there were 9 questions with 3 edges to find and 3 questions with 2 edges to find, the minimum number of selections was 33 for each view. Because there were three views for each of the questions, the total minimum number of selection per group was 99. The average number of selections made by a pair in the block condition was 125.3, which corresponds to an overhead of 25%. The overhead was higher for pairs in the token condition: 145.8 selections on average, which represents an overhead of 45% ($p<0.05$, F[1,21]=5.4).

Per view

The number of selections and unselections also varied according to the view. The number of clicks for all the views showed an overhead compared to the minimum number of clicks required to complete all the exercises correctly. However, the overhead differed in its proportion: the top view showed an overview of 10.8%; the front view, 45.2%; and the side view, 61.0%.

Strategies

Most of the groups adopted a ”group-by-view” strategy, meaning that they searched for all the edges on one view before moving on to the next one. The most common strategy was to find the edges on the plan view, then the front view, and finally on the side view (17 groups). Three groups adopted the exact reverse strategy: side view first, then front view, and finally the top view. The variety of strategies makes it difficult to identify whether one strategy was correlated with a better performance. It is however worth noting that participants never used a ”group-by-edge” strategy and that the condition did not lead participants to adopt different strategies.

Activity duration

All activities

The average duration to complete all the activities was 20.5 minutes (SD: 5 minutes and 35 seconds). Completing the activities in the block condition took sightly less time than in the token condition (19.4 vs. 21.9, $p>0.05$, F[1,21]=1.08). As indicated by the rather large standard deviation, there were major differences in speed between the groups, especially in the token condition: the slowest group completed the activities in 34 minutes, while the fastest group only took 12 minutes.

Single activity

The average activity duration slightly decreased over time. However, the most noticeable difference was between the first activity and the rest of them, hinting that during the first one or two activities, participants had to get acquainted to the system.

Rotation

In both conditions, the user could apply a rotation to the 3D object by rotating the physical object they were given (either the token or the block). Rotating the object may be of interest to position the block so that a specific edge is more easily identified on a given view. The rationale for looking at the total amount of rotations is that a harder condition might have required the apprentices to rotate the blocks more. However, there was no significant difference in the total amount of rotation between the conditions.

Performance by block

In total 7 different blocks were used over the 12 activities. The blocks are shown in Figure 11 at the very end of this article. The performance by block is shown in Figure 9 as a ratio of correct edges.

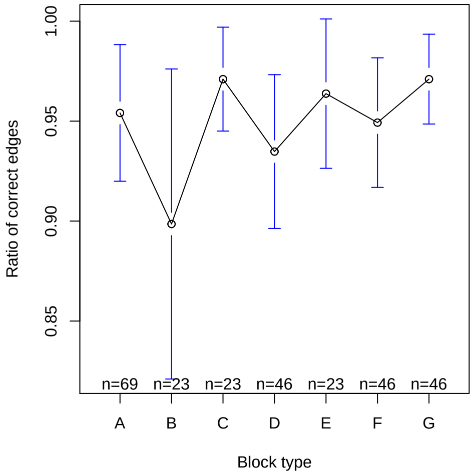


Figure 9. The ratio of correct edges per block type.

The only block that really stood out is the 'B' block. There are two possible reasons for the lower performance with this block. The first one is that it was used only once over the 12 activities and was placed in second position. As we have seen above, the performance improved with time, so the early placement of this block might explain part of the lower performance. A second reason is that this block has a high degree of symmetry (3 symmetry planes). A high degree of symmetry may make it harder to find reference points when trying to map the 2D and the 3D representation.

The influence of the symmetry of a block on the performance is shown in Figure 10. The degree of symmetry is the number of symmetry planes on a block. There is no interaction effect between the symmetry and the view on which the edge must be found ($p>0.05$, F[4,797]=0.48). There is also no interaction effect of the condition and the symmetry on the performance ($p>0.05$, F[2,801]=0.41). However, a higher degree of symmetry leads to a significantly lower performance ($p<0.05$, F[2,801]=104.0). Moreover, Figure 10 indicates that the degree of symmetry has a larger impact than the view on the performance.

SUMMARY AND DISCUSSION

There were three main outcomes from this study: (1) the difference between the two conditions in terms of performance during the treatment and their similar strong positive learning outcomes; (2) the difference of difficulty between the 3 views;

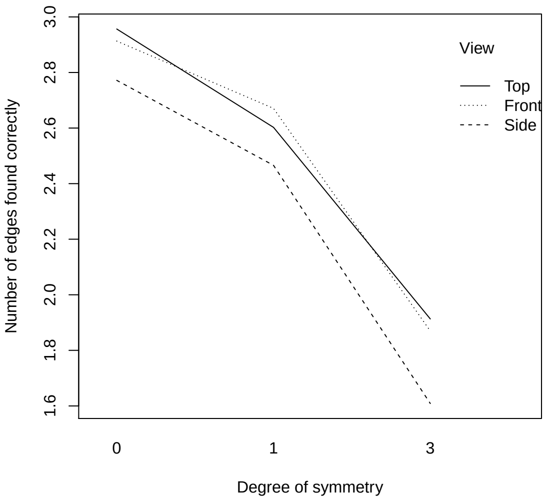


Figure 10. Number of edges found correctly by the degree of symmetry of the blog to which the edge belongs and by the view on which an edge must be found. The degree of the symmetry is the number of symmetry planes on the block.

and finally , (3) the link between the degree of symmetry of a block and the difficulty to find an edge on the block.

Differences between the two conditions

The main goal of this study was to examine the impact of a tangible representation, as opposed to a virtual representation, when solving a spatial skills related task. There was a performance difference between the token and the block condition during the activities. Participants in the block condition completed more activities correctly, and found more edges correctly overall. Their scores significantly improved over the course of the activities, whereas the improvement of participants in the token condition was not significant.

However, despite the differences observed during the treatment, there was no statistically significant difference in the learning gain between the block and the token condition, as measured by the pre-test and the post-test. Indeed, the participants performed in both conditions significantly better in the post-test than in the pre-test. Participants in the block condition improved slightly more than those in the token condition, but not significantly. The slight ceiling effect observed could explain the lack of statistical significance, and it may be that the differences observed between the two conditions would have been larger with more difficult questions and a longer treatment.

In both conditions, participants used the same "group-per-view strategy". Participants in the block condition were slightly faster at solving activities and did significantly fewer trials (click). This, together with the higher success rate of participants in the block condition, indicates that doing the exercises in the block condition was easier than doing them in the token condition. Some participants who informally tested both conditions after the experiment confirmed that to them, having the tangible block as a 3D representation made the task easier than looking at the virtual 3D representation.

Making a task easier reduces the cognitive effort required by the student, but does not necessarily benefit learning. On one hand, learning might be inhibited if the task is facilitated such that the cognitive mechanisms which trigger learning are removed. This is the case to some extent when learning to bike with training wheels: biking is easier, but the sense of balance is not acquired. On the other hand, learning might be increased if the process of accomplishing the task is made easier but the cognitive mechanisms essential for learning remain.

In this study, although the block condition was easier, it did not inhibit learning: the improvement in the block condition was larger during the treatment and the learning gain between pre-test and post-test was slightly higher. The main difference between the two conditions was the cognitive process required to create a mental representation of the object. This suggests that in this learning task the block helped the participants create a mental model without inhibiting the key cognitive learning mechanisms. This is of interest for the development of future tangible learning environments, since it means that tangibles can be beneficial when there is a need to create a mental representation of an object.

Particularity of the side view

An analysis of the performance for each of the 3 views (plan, face, and side) revealed that the side view was more difficult than the other two views. This was the case both in the tests and during the 12 treatment activities. This is consistent with the existing literature on spatial skills which states that the difficulty of a mental rotation is proportional to the amplitude of the rotation (e.g. [13, 4]). Since the side view requires a 90 degree mental rotation, it is expected to be more difficult than the two other views which require a smaller mental rotation for the participant to mentally align the 3D representation of the object with the corresponding orthographic projections.

An analysis of the relative learning gain between the pre-test and the post-test showed that the side view, while the hardest one, was also the one on which participants improved the most. It was also only on the side view that the number of mistakes during the treatment decreased significantly. This is a meaningful result from a pedagogical point of view since it shows that our system can help students improve where they need it most.

The side view further crystalized the differences between the two conditions: participants in the token condition made significantly more mistakes on the side view, whereas the number of mistakes in the other views was comparable for the two conditions. There are two plausible explanations for this. One is that in the block condition, participants could pick up the block and move it in space, in other words they could do the rotations physically instead of doing them mentally. However, such interactions did not occur very often (2 groups). Another explanation is that the block gave the participants a better representation of the object, leading to an easier representation of what the corresponding orthographic projection would be.

Symmetry of the object

Some blocks were harder to deal with than others. The higher the degree of symmetry of a block, the lower the performance on this block. Intuitively, this result can be explained by the fact that the higher the degree of symmetry, the more difficult it is to find reference points on the object. Therefore, it becomes harder to figure out the orientation of the object on each view, and by extension harder to find a specific edge. Since this is valid for all three views, it is of no surprise that there was no interaction effect between the view and the degree of symmetry. Note however that this is not necessarily intuitive, since in other types of geometrical exercices the difficulty is often increased by using a block of higher geometrical complexity (see e.g. [19]).

CONCLUSION

We studied the impact of TUIs on the training of spatial skills. In a study involving 46 participants, we investigated the effect of being able to physically visualize and manipulate the object, as opposed to just manipulate a virtual representation of the object using a simple token. Two main results came out of this study. First, in both conditions the participants' spatial reasoning skills improved significantly after solving exercises on the TUI, showing that TUIs can benefit learning, but there was no significant differences between the two conditions. Second, during the experimental task, participants using the tangible object performed significantly better than those using the token. This was especially the case when the difficulty of the problems increased – i.e. when the degree of symmetry of the block was higher and the rotation required larger.

Similarly to some recent work [2], these results emphasize the impact that design decisions for TUIs may have on improving a particular skill. There are many design dimensions that have to be taken into consideration when designing a TUI for learning purposes. In our study, we focused on the object representation dimension, keeping the mode of interaction constant across both conditions. Changing the object representation alone led to significant differences in the performance of participants during the experimental task. In the case of spatial skills the tangible object representation is a key element of the interface. In other contexts, other design dimensions might be of more importance. For example, in a TUI designed to learn about construction materials, the mass and the texture of the objects would be more meaningful than the object representation. We believe that this work therefore contributes to the debate about whether TUIs can improve the learning outcomes by emphasizing the importance of the relationship between design aspects of the TUI and the specificities of the learning domain.

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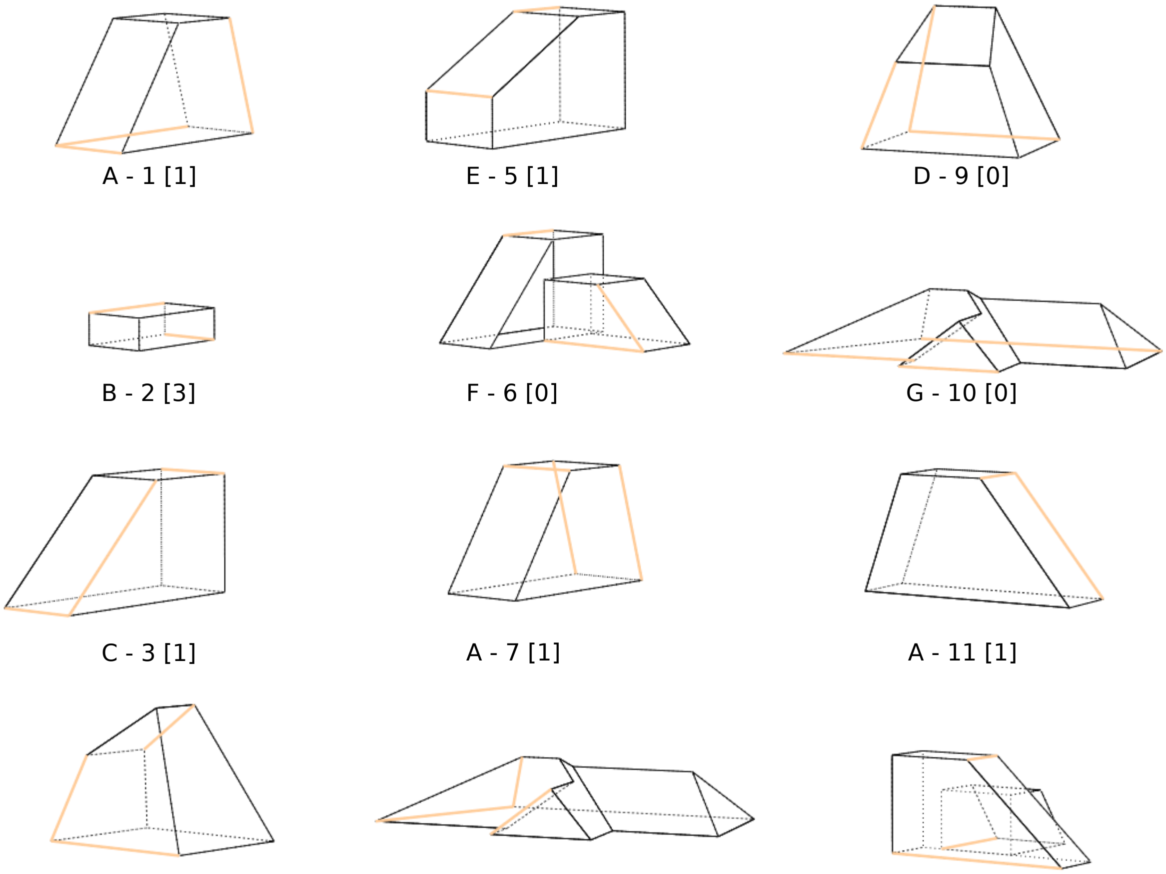

A - 1 [1]

E - 5 [1]

D - 9 [0]

B - 2 [3]

F - 6 [0]

G - 10 [0]

C - 3 [1]

A - 7 [1]

A - 11 [1]

D - 4 [0]

G - 8 [0]

F - 12 [0]

Figure 11. The 12 exercises solved by the participants. The letter under a figure indicates the block identifier. The first number is the rank of the question and the number in brackets is the degree of symmetry of the block.