Comparing the Benefits of a Tangible User Interface and Contrasting Cases as a Preparation for Future Learning

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Abstract: In this paper we describe an experiment that compared the use of a Tangible User Interface (TUIs) in a constructivist fashion with a traditional learning activity. We carried out an experiment (N=40) with a 2x2 design: the first factor compared traditional instruction ("Tell & Practice") with a constructivist activity (using the Preparation for Future learning framework; PFL). The second factor contrasted state-of-the-art PFL learning activity (i.e., students studying Contrasting Cases) with an interactive tabletop featuring digitally-enhanced manipulatives. In agreement with prior work, we found that students who followed the PFL activity achieved significantly higher learning gains compared to their peers who followed a traditional "Tell & Practice" instruction (large effect size). A similar effect was found in favor of the interactive tabletop compared to the Contrasting Cases (small to moderate effect size). We discuss implications for designing constructivist activities using new computer interfaces.

Introduction

Over the past decades, educational researchers have been advocating constructivist activities to foster meaningful and deeper learning in STEM. This movement was an answer to the behaviorist movement that has been prevalent in educational circles for decades (cf. "programmed instruction" Skinner, 1986), which promoted repetitive exercises to reinforce students' proficiency at following particular procedures, such as applying a particular formula or algorithm to solve a mathematical problem. At least among researchers, over the last decades, there was widespread acceptance of constructivist theories. Constructivism "surfed" on a wave of optimism for many years before educators and researchers realized how difficult it was to design effective discovery learning activities. More recently, some scholars directly attacked this theoretical framework, calling it a failure (Kirschner, Sweller & Clark, 2006). The goal of this paper is to present a case of a successful application of constructivist theories and an analysis of the mechanisms that led students to achieve higher learning gains over traditional instruction. Additionally, we provide evidences that new technologies, such as Tangible User Interfaces (TUIs) have the potential to efficiently support constructivist activities.

Theoretical framework

The general theoretical framework of this paper is the idea that people learn best by using their prior knowledge to make sense of a new learning material (Piaget, 1928); that is, students actively construct knowledge (as opposed to just receiving and accumulating it). In particular, it has also been shown that building artifacts (digital or physical), and going through a process of debugging mental models by externalizing them using different media, are especially powerful (Papert, 1980). This is a major contrast with the traditional "Tell & Practice" instruction (T&P) used in most classrooms, where students are first exposed to the "truth" and then asked to practice their understanding of a particular concept on a series of exercises. Even though this constructivist view of the human mind is generally accepted among the scientific community and is seen as being beneficial to students' learning, there are two main limitations when implementing this approach.

First, students need to have some pre-existing knowledge that they can use to make sense of new concepts; this approach falls short if students don't have any prior experiences in the domain taught or if they don't have the opportunity to build some foundations prior to a lecture. It is likely that students in this situation will resolve themselves to take plenty of notes and memorize as much of the teacher's lesson as possible with the hope that they will understand the content later. This scenario favors rote memorization and hinders transfer (Bransford & Schwartz, 1999). One framework that attempts to mitigate this problem is the Preparing for Future Learning framework (PFL; Schwartz & Bransford, 1998). The idea is to provide students with an open-ended activity prior to the lecture to allow them to construct some intuition about the concepts taught. Schwartz and Bransford argue that Contrasting Cases (CC) are ideal candidates for this task. CC allow students to separate surface and deep features of a problem and provides them with an opportunity for generating self-explanations (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). This framework motivated the first comparison of our study between a PFL-style constructivist activity and a more standard T&P instruction.

The second limitation is that efficient discovery learning activities are notoriously difficult to design (De Jong & Van Joolingen, 1998). It takes serious engineering and designing efforts to create an activity that engages and motivates learners, target specific learning goals, has affordances for conceptual reflection, works with both high-achieving students and less proficient ones, and allow for productive failure (Kapur, 2008). Contrasting Cases, for instance, are an especially difficult case. Many believed that computer simulations and programming environments would bring a solution to this problem, by providing engaging virtual environments where students could explore rich micro-worlds, and experiment with scientific and mathematic phenomena in a hands-on fashion (Papert, 1980). De Jong and Van Joolingen (1998) conducted a review of the various empirical studies using computer simulations as discovery-learning tools and found some mixed (but mostly positive) effects on students' learning. We build on this prior work and extend this idea to new interfaces appropriate for hands-on learning: Tangible Users Interfaces (TUIs). TUIs are computer systems that replace the traditional mouse and keyboard with physical objects, detect their states (such as their location) and provide a feedback loop to replace the screen with an augmented reality system (for instance by using a projector and displaying additional information directly on the objects). TUIs have specific affordances for constructivist learning, by supporting students' exploration of a complex domain (Schneider, Jermann, Zufferey, & Dillenbourg, 2011), students' engagement and enjoyment (Shaer & al., 2011), small-group collaboration (Schneider & al., 2012) and hands-on activities in co-located settings (Dillenbourg & Evans, 2011).

Our goal is to address those two limitations. First, we want to replicate previous results (Schneider, Wallace, Blikstein & Pea, 2013) showing that providing students with an opportunity to build prior knowledge with a TUI before following a more standard type of instruction is beneficial to learning (compared to a traditional "tell-and-practice" approach, where students are first taught some concepts and then practice their understanding of those concepts on a TUI). Secondly, we want to see how TUIs compare to contrasting cases in terms of preparing students for future learning: in other words, is it worth spending time and energy building interactive hands-on activities? Do they provide any benefits compared to traditional "pen and paper" activities?

General description of the experiment

We designed the following experiment to investigate those two lines of research: in the control group, half of the participants first read an abridged version of a textbook chapter on the human visual system and then completed another activity where they had to apply their new knowledge ("T&P" condition). In the treatment group, the other half of the participants first discovered those concepts in a hands-on activity and then learned about them in a more traditional way, i.e., by reading an abridged textbook chapter ("Invent" condition). Based on the PFL framework, our main hypothesis is that the treatment group should achieve higher learning gains compared to the control group. Additionally, we crossed another factor in our experimental design: the hands-on activity was either a set of Contrasting Cases (CC) or a Tangible User Interface (TUI). We did not have a strong hypothesis regarding this comparison, but expected the TUI group to slightly outperform the CC group on the final learning test; as mentioned above, previous work suggests that TUIs facilitate exploration, increase engagement and support collaborative problem-solving in small groups. Participants were counter-balanced across conditions. We designed measures to look at three potential predictors for learning: engagement (using a questionnaire with validated psychometric properties), curiosity (by having students list all the questions they would like to see answered after the first activity), and quality of their mental models (by asking students to draw a model summarizing their understanding of the topic taught after the first activity). Our goal was to see if students would differ on those measures between our different conditions.

Concerning those measures (engagement, curiosity, quality of their mental models), our hypotheses are as follows: first, the main difference between the "invent" and "T&P" groups should be about the quality of students' mental model and their curiosity. Since the PFL framework is about helping students construct some prior knowledge, we believe that the PFL activity should help them build a mini-theory of how the human visual system works; this difference should be reflected in their drawings after the first activity. In this process, students should be more likely to ask themselves questions and develop their curiosity about the topic taught. This should then help them make sense of a standard instruction (reading a text about the visual system). On the other hand, we expect students in the control group ("T&P") to focus on memorizing the content of the text and spending their time recalling this information when completing the second activity (i.e., using the TUI or working on the CC). Secondly, we expect the main difference between the TUI and CC groups to be about their levels of engagement. Since TUIs have been shown to promote exploration and hands-on learning (Schneider, Jermann, Zufferey, & Dillenbourg, 2011), we believe that the physicality of the system should invite students to be less intimidated by the complexity of the domain taught and explore the problem space to a greater extent. Those two hypotheses motivated the use of measures described below (i.e., middle test measuring the quality of the students' mental model and their curiosity, and a questionnaire measuring their engagement). Finally, we did not have any hypothesis regarding an interaction effect between our two factors (i.e., we don't have any reason to believe that CC or the TUI should have a differentiated effect on students in the PFL or T&P conditions.)

Methods

Participants

40 students from a community college participated in this study (13 males, 27 females; mean age = 21.28, SD = 4.08). Students signed up for the study as part of a psychology class. The only prerequisite for participating was to have no prior knowledge on the topic taught (neuroscience and the visual system). Students were randomly assigned to each experimental condition.

Material

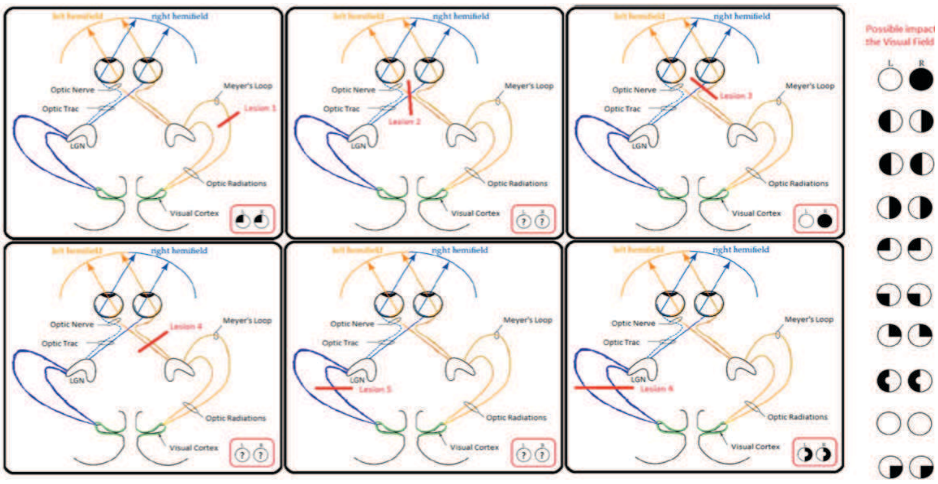

Figure 1: The set of contrasting cases used in the study. Answers are given for diagram 1, 3 and 6. Potential answers for the remaining cases are shown on the right column.

This study included three different activities (Fig. 3). In the "invent" condition, students first explored the domain taught with either a TUI or a set of contrasting cases. The TUI is described below (Fig. 2); the CC (Fig. 1) included 6 diagrams of the human brain, each one featuring a different lesion. Half of the CC showed the correct answer to students (i.e., case 1, 3 and 6). The right column showed potential answers for the remaining cases. After finishing the first activity, students answered the following two questions: 1) "By the end of this first activity, what are the questions that you would like to see answered about the way the human brain processes visual information?" and 2) "Please draw a simple model that summarizes your understanding of the way the human brain processes visual information." During the second activity, students read an abridged version of a textbook chapter explaining how visual information is processed in the human brain (available at: http://goo.gl/47RIwv). Finally, they took a post-test that included questions on the terminology used (students had to correctly label different brain regions and neural pathways), on the effect of various lesions on the visual field (given a particular lesion, students had to draw its effect on a person's visual field), and on more general scenarios involving human vision (transfer questions). Finally, we asked them to fill the engagement questionnaire designed by O'Brien, Toms, Kelloway, and Kelley (2008). This questionnaire was developed for researchers in HCI (Human-Computer Interaction) and measures six dimensions of an activity that relates to users' engagement (33 items on a Likert scale): focused attention (9 items; e.g., "I forgot about my immediate surroundings while doing X"), perceived usability (8 items, e.g., "I felt frustrated / discouraged / annoyed while doing X"), aesthetics (5 items, e.g., "X was aesthetically appealing), endurability (5 items, e.g., "I consider my experience with X a success"), novelty (3 items, e.g., "I continued to do X out of curiosity") and involvement (3 items, e.g., "I was really drawn into X"). In the T&P condition, the order of the learning phases was reversed (students first read the text and then completed the TUI or CC activity).

The TUI used in this study is an improved version of a system previously developed in our lab (Schneider, Wallace, Blikstein & Pea, 2013), called BrainExplorer. BrainExplorer (Fig. 2) allows students to physically manipulate a small-scale replica of a brain while an interactive tabletop displays visual pathways between brain regions. Users can then cut those pathways to create lesions and observe their effect on the visual field of a subject. Two eyes (with a webcam) captured the field of view of this brain and shows occlusions on the corresponding visual field.

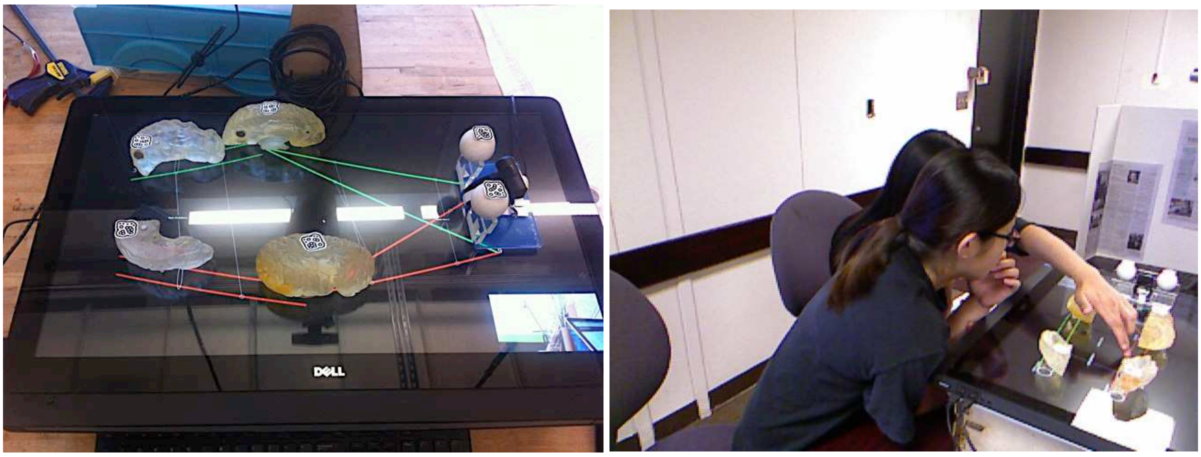

Figure 2. The TUI used in this experiment (BrainExplorer). The system on the left shows the tangibles that students can manipulate with the field of view of this brain (bottom right corner of the table). The image on the right shows two students interacting with the system during our study.

Design

We used a 2x2 between-subjects experimental design (Fig. 3). The first factor had two different hands-on conditions: the tangible interface and contrasting cases. The second factor sequenced the two learning activities in different ways: either with the hands-on activity first (“invent” → “read”) or second (“T&P”).

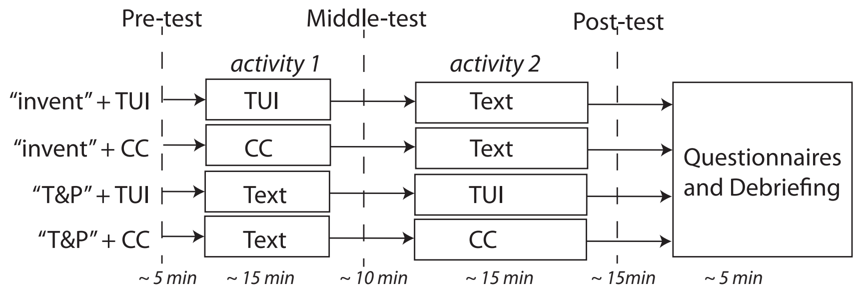

Figure 3. The four experimental conditions of our study (factor 1 = "Invent" versus "Tell-and-Practice" (T&P); factor 2 = Tangible User Interface “TUI” versus Contrasting Cases “CC”)

Procedure

The experimenter ran students in groups of two in a private room. Upon their arrival, the experimenter welcomed them and told them that they would complete two small learning activities in groups. They were also told that the topic taught was about neuroscience and the human visual system. After filling a pre-test, students completed two learning activities: In the “invent” condition, they first did the hands-on activity (i.e., TUI or CC) and then read a text about the visual system. In the “T&P” condition, they first read the text and then practiced their understanding of the topic on the hands-on activity. A second factor was crossed with those two conditions: students either worked with the CC or TUI for the hands-on activity. Thus, referring to Figure 3, students in the “invent” + CC condition discovered those concepts with contrasting cases and then read a text. Students in the “invent” + TUI condition followed the same procedure except that they used the TUI instead of the CC. Students in the T&P + CC first read a text and then applied the concepts they just learned on a set of CC. Students in the T&P + TUI followed the same procedure except that they reinforced their understanding of the visual system by using the TUI. Each activity was 15 minutes long.

Between the two activities, the experimenter gave students two questions to answer individually (10 minutes): first, they had to list the questions that they wanted to see answered about the human visual system after the first activity (i.e., a measure of curiosity); second, they had to draw a model summarizing their understanding of the concepts taught (see the “material” section for more information)., students individually completed a post-test (15 minutes) and were thanked for their participation.

Coding

The pre-tests and post-tests were coded in a binary fashion (1 point for a correct answer, 0 point for an incorrect answer). For the middle test, we counted the number of questions students had and applied a simple rating scheme to their models: 1 = no useful information shown; 2 = some useful information, mostly about the terminology used (no or little conceptual understanding of the effect of lesions on the visual field); 3 = significant signs of understanding of the way visual information is processed by the human brain. Figure 4 provides an example for each category. Only one researcher coded the tests and the drawings, because the coding schemes were simple and straightforward to apply.

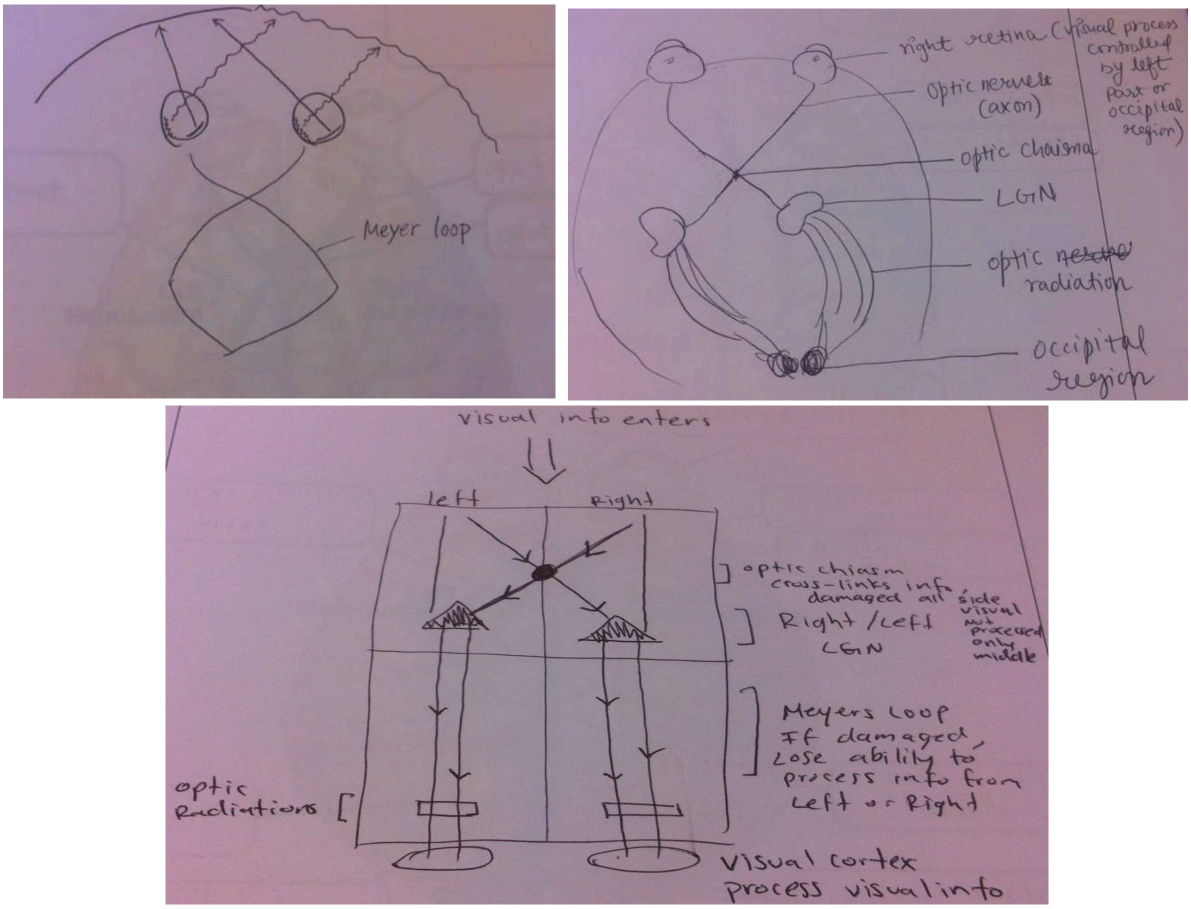

Figure 4. Three examples of models drawn by our participants. The model on the top left received 1 point (= no or little useful information); the one on the top right received 2 points (= some useful information, mostly about the terminology); and the one on the bottom received 3 points (= clear signs of conceptual understanding).

Results

Since our samples are not independent (i.e., members of a dyad influenced each other) and since the intraclass correlation for the learning test is significant ($p < 0.001$; Kenny, Kashy & Cook, 2006), it is advised to conduct analyses at the dyad level. Since this reduced our statistical power, we will also report results where $p < 0.1$ with a moderate effect size. We also checked students' Grade Point Average (GPA), since populations in community colleges are known to be heterogeneous. Because there was an interaction effect: $F(1,16) = 4.46$, $p = 0.049$ (Fig. 5, left side) between the two levels of our factors, we used GPA as a covariate for the following analyses.

Learning gains

The results supported our two main hypotheses. Since participants did not score any points on the pre-test, we only considered their results on the post-test. Scores are shown on Figure 5 (right side). An ANCOVA revealed that students in the "Invent" condition outperformed students in the "T&P" condition: $F(1,16) = 15.45$, $p < .001$, Cohen's $d = 1.41$ (for the "invent" group, $M = 12.95$, $SD = 3.15$; for the "T&P" group, $M = 7.85$, $SD = 4.06$). Additionally, students using the TUI outperformed students in the CC group: $F(1,16) = 5.32$, $p = .036$, Cohen's

d = 0.48 (CC: M = 9.35, SD = 3.90; TUI: M = 11.45, SD = 4.74). All distributions were checked for normality and homogeneity of variance.

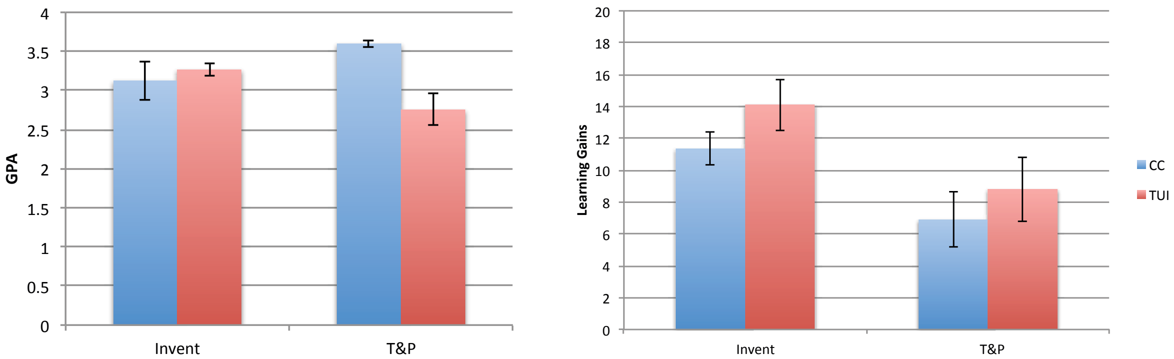

Figure 5. Left: distributions of students' GPA. Right: Results on the learning test (Standard Errors shown). CC stands for Contrasting Cases, TUI for Tangible User Interface and T&P for "Tell-and-Practice".

Curiosity and mental models

Additionally, we looked at the effect of our two factors on the results of the middle-test (i.e., the number of questions students would like to see answered about this topic – a crude measure of curiosity – and the quality of the model they drew). For the first factor, we found that students in the "Invent" group created significantly higher quality models compared to the students in the "T&P" group: $F(1,16) = 7.38$, $p = .016$, Cohen's $d = 1.32$ (for the "invent" group, $M = 2.00$, $SD = 0.56$; for the "T&P" group, $M = 1.35$, $SD = 0.41$). There was no significant difference in terms of the number of questions they asked themselves: $F(1,16) = 2.75$, $p = .118$, Cohens'$d = 0.81$. For the second factor (TUI vs CC), both comparisons were not significant ($F < 1$). We then correlated those two measures with our main dependent variable. Both measures were significantly associated with higher learning gains: $r(20) = .40$, $p = .043$ for the number of questions students asked themselves and $r(20) = .55$, $p = .007$ for the quality of students' model.

Engagement

Finally, we looked at the engagement questionnaire administered at the end of the study (see Table 1). We found that participants in the "Invent" condition were more engaged (aggregate measure of all the items) than the students in the "T&P" group: $F(1,16) = 6.1$, $p = .025$, Cohen's $d = 1.05$. Results were significant on the "endurability" sub-dimension ($p < .05$) and marginally significant on the "Focus" ($p = .096$), "involvement ($p = .068$), novelty ($p = .066$) and aesthetics ($p = .071$) sub-dimensions. Similarly, students in the "TUI" group were marginally more engaged compared to the "CC" group: $F(1,16) = 3.4$, $p = .064$, Cohen's $d = 0.80$. They found the TUI to be more usable ($p < .05$) and rated the endurability and aesthetics' dimensions marginally higher ($p = .108$ and $p = .114$, respectively). Across all participants, being engaged was significantly correlated with higher learning gains ($p = .015$); more specifically, involvement and endurability were the only sub-dimensions significantly correlated with students' learning ($p = .011$ and $p = .03$, respectively).

Table 1: Engagement scores between our experimental groups.

	Focus	Involvement	Novelty	Endurability	Aesthetics	Usability	Engagement
TUI vs CC	$F < 1$	$F < 1$	$F < 1$	$F = 2.9$ $p = .108$ $d = 0.45$	$F = 2.8$ $p = .114$ $d = 0.73$	**$F = 5.4$** **$p = .033$*** **$d = 0.85$**	$F = 3.4$ $p = .064$ $d = 0.80$
Invent vs T&P	$F = 3.1$ $p = .096$ $d = 0.45$	$F = 3.8$ $p = .068$ $d = 0.71$	$F = 3.9$ $p = .066$ $d = 0.72$	**$F = 4.7$** **$p = .045$*** **$d = 0.77$**	$F = 3.7$ $p = .071$ $d = 0.70$	$F < 1$	**$F = 6.1$** **$p = .025$*** **$d = 1.05$**
Correlation with learning	$r = .33$ $p = .152$	**$r = .56$** **$p = .011$***	$r = .33$ $p = .154$	**$r = .49$** **$p = .030$***	$r = .36$ $p = .122$	$r = .21$ $p = .380$	**$r = .53$** **$p = .015$***

Notes: Row 2 and 3: MANCOVA between the two levels of our two factors on the dimensions of the engagement questionnaire. Row 4 reports correlations with students' learning gains. Degrees of freedom are indicated as above: $r(20)$ for the correlations, and $F(1,16)$ for the F-tests; d is Cohen's d.

Linear regression

We ran a linear regression to find how much variance of the learning gains our main predictors could explain (i.e., number of questions on the middle-test, complexity of students' mental model, endurability, involvement). We found that the quality of students' mental model was the strongest predictor (β = .43), followed by the endurability variable (β = .30), students' involvement (β = .22) and curiosity (β = .12). Altogether, these four variables explained more than half of the variance of students' learning gains: R^2 = .58, F(4,18) = 4.78, p = 0.012 (Table 2).

Table 2: Linear regression with students' learning gains as the dependent variable (R^2 = .58)

Variable Name	β	*t-test*
Endurability ("students' perception of success")	.304	t(15) = 1.35, p = .199
Involvement	.224	t(15) = 0.94, p = .361
Curiosity (Number of Questions Asked)	.119	t(15) = 0.60, p = .555
Quality of Students' Mental Model	**.434**	**t(15) = 2.34, p = .035***

Discussion

The main goal of this paper was to show that technologically enhanced hands-on activities (i.e., TUIs) have the potential to increase students' learning in traditional constructivist activities. We also wanted to replicate previous results showing the benefits of creating prior knowledge before receiving formal instruction. Our results suggest that PFL activities have a large effect on students' learning. When prompted to explore a domain by themselves before reading an abridged textbook chapter, students developed more refined mental models, became more curious, more engaged and perceived themselves as being more successful (compared to the students in the T&P group); additionally, those differences were associated with higher learning gains. The fact that students created better models based solely on their analyses of the contrasting cases or by interacting with the TUI is promising: it shows that providing students in the control group (T&P) with an already complete set of diagrams prevented them from creating their own model; worse, they didn't even internalize the ideal model from the textbook in a proper way. Additionally, our results suggest that using a Tangible Interface as a preparatory activity has a positive effect on students' learning compared to studying CC. Participants learned more when using the interactive system and felt more engaged compared to the CC. Marginally significant effects suggest that students using the TUI felt more successful with the task ("endurability"), which was correlated with higher learning gains. They also found the activity to be more aesthetically appealing and the TUI to be more usable, but those measures were not associated with higher learning gains.

However, those measures do not provide us with the full picture; it is likely that the TUI had a beneficial effect on students' learning beyond their level of engagement. We suggest a few hypotheses to be tested in future work. First, BrainExplorer, and similar TUI-based exploratory systems, provide students with "on-demand" or "just-in-time" information about the visual system. From our qualitative observations, we saw students develop different strategies when using the system. Some were more confortable using a "bottom-up" approach (i.e., they started by analyzing the pathways from the eyes to the LGN, and then from the LGN to the visual cortex); some others followed the same approach, but in reverse; finally some students started by making as many lesions as they could, and then focused on more specific regions. In future work, we plan to compare the variety of strategies used in both conditions (TUI vs. CC) to test this hypothesis. Secondly, it is possible that using a TUI had an indirect effect on students' collaboration, which in turn had a positive effect on learning. For instance, it is conceivable that students found it easier to explore the problem space together (Schneider, Jermann, Zufferey & Dillenbourg, 2011), share information and build hypotheses (Shaer & al., 2011) with the TUI. We plan to code students' quality of collaboration and correlate those measures with learning gains in future work. Finally, It is possible that the results above were caused by a novelty effect; this is the most natural explanation for the significant effect found between TUI and CC, since most students had likely not interacted with a tangible interface in the past. However, the statistical analyses performed on the "novelty" dimension of the engagement questionnaire did not support this explanation. Future work will look more closely at this possible confounding variable.

It is worth mentioning that we do not take those results as evidence that TUIs are better learning activities than CC beyond the scope of this experiment. Both activities can take many forms, and their efficiency is strongly influenced by a variety of design choices. Our findings merely suggest that the TUI introduced in this paper (BrainExplorer) seemed to promote higher learning gains compared to the CC presented above. In summary, more analyses are needed both in collecting qualitative segments suggesting explanation for the higher learning gains found in the TUI (versus CC) condition, and in analyzing the logs of the system to determine students' strategies when exploring BrainExplorer.

Conclusion

This paper presented a successful application of the "Preparing for Future Learning" framework to education in a complex field of knowledge (neuroscience). Our findings suggest that, under certain circumstances, minimally guided instruction can be beneficial to learning. Our measures suggest that our intervention dramatically influenced the quality of students' mental models, which had a positive effect on their learning gains. This measure, associated with students' curiosity, involvement and perception of being successful at the discovery task, predicted more than half of the variance of their scores on the post-test. This shows the positive effect of using constructivist-inspired preparatory learning activities for learning scientific concepts. Those results, combined with others (e.g., Schwartz & Bransford, 1998; Schwartz & Martin, 2004), confirm that there is still a considerable gap between educational research (that advocates a constructivist view of students' learning) and regular classroom instruction (that still prevalently use a "T&P" framework). The contribution of this paper is to propose a step toward closing this gap. We suggest combining the affordances the new technologies (e.g., TUIs) with existing educational frameworks (e.g., PFL) to provide students with compelling, carefully-crafted hands-on learning experiences that prepare them for future learning.

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