Chapter 12
Preparing Students for Future Learning with Mixed Reality Interfaces

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Abstract In this chapter, I explore how new learning environments, such as mixed reality interfaces (i.e., interfaces that combine physical and virtual information), can prepare students for future learning. I describe four controlled experiments that I have conducted over the years where students learned complex concepts in STEM and where a Tangible User Interface created a "Time for Telling". This is followed by a summary the findings, a discussion of the possible mechanisms for the effect found in those studies, and a suggestion of design guidelines for creating this type of constructivist activities. I conclude by discussing the potential of mixed reality interfaces for preparing students for future learning.

Keywords Tangible user interfaces · Preparation for future learning
Augmented reality

12.1 Introduction

Over the past decades, new advances in Human–Computer Interaction (HCI) have radically changed the way we interact with computers. Technology has become more pervasive, ubiquitous and intuitive to use. The possible inputs are now multi-modal: users can talk, touch, gesture or even use their gaze to control a computer. The output is no longer limited to a screen; Augmented Reality (AR) systems can overlay digital information on the perceived physical world, and Virtual Reality (VR) can immerse users into virtual worlds. The lines between digital and physical worlds have blurred, which dramatically increases the design space for creating new types of immersive learning experiences. The scenarios that students can experience in mixed-reality/virtual worlds are many and can result in

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effective, efficient and engaging learning. They were not possible before the advent and maturation of these powerful digital technologies.

It seems logical to assume that those experiences have an untapped potential in education. It also makes sense that they cannot—and should not—be used to replace all types of instruction. Rather, we would expect those experiences to be used strategically to maximize learning. But what are the theories that could inform when and how those immersive learning experience would benefit learners the most? In this chapter, I explore one possibility by leveraging a framework called Preparing for Future Learning (PFL). The PFL framework suggests that particular kinds of experiences can help students build prior knowledge in specific ways, which will then help them take advantage of subsequent instruction. The focus of this chapter is to enhance those experience through new technologies.

In this chapter, I first introduce new types of computer interfaces that offer interesting potential for education (Natural User Interfaces, and more specifically Tangible User Interfaces) and describe their affordances for learning. In Sect. 12.3, I introduce the PFL framework and its implications for designing learning environments and new pedagogical scenarios. Section 12.4 is a summary of empirical findings that highlight the benefits of adopting this constructivist approach. Finally, I discuss implications of those results for designing innovative learning environments.

12.2 Natural User Interfaces (NUIs)

If we look back at the first computers in the 80s, it is astonishing to think about the steepness of their learning curve. The command line interface (CLI) appeared first, where the keyboard was the only available input. It forced users to memorize complex mapping between keystrokes and actions: for instance, the VI text editor—which is 40 years old, but still used today—required users to press the letter h, j, k, l to move left, down, up, right on the screen, i to insert characters, d to delete them, and so on. Even though VI is still among the most powerful text editors available to programmers today, it still takes a massive amount of time and energy for any given user to gain fluency in its use. The introduction of the graphical user interface (GUI) has allowed users to point at elements on a screen with a mouse, and reduced this learning curve by an order of magnitude. Instead of memorizing complex keystroke sequences, users can merely point and click. Over the past decade, this learning curve has become almost non-existent. Toddlers, for instance, have no issues interacting with touch-screen tablets. The emergence of new kinds of interfaces, called natural user interfaces (NUIs), have transformed the technological landscape. NUIs are defined as "systems for human-computer interaction that the user operates through intuitive actions related to natural, everyday human behavior". In short, there is no need to learn specific mappings between inputs and outputs on a NUI: the content is the interface (Wigdor & Wixon, 2011). NUIs include touch screens (e.g., the IPad™), gesture-based systems (e.g., the Kinect™

sensor), voice-controlled programs (e.g., Cortana/Siri™), gaze-aware interfaces (e.g., TobiiX™), and brain-machine interfaces that read neural signals and use programs to translate those signals into inputs.

This revolution has dramatically changed the way we interact with computers, and has implications for designing educational activities as well. Designers can create rich scenarios for wider audiences who, for instance, could not use standard interfaces very well—such as very young children, people with physical disabilities as well as individuals who are less comfortable with technology. This also means that we can redirect the burden of learning a computer interface toward more useful cognitive processes. Instead of having students struggle with memorizing mappings and menus, they can focus their energy on the learning task. Finally, it allows instructional designers to create multi-modal interactions. Some domains are best explored through gestures and body movements, while others benefit from collaboratively and verbally exploring a subject. New interfaces (gesture-based, brain-controlled, gaze-aware, voice-controlled, and so on) have particular affordances that could benefit learners in different ways. In this chapter, I focus on one type of NUI that has interesting properties for educational applications: tangible user interfaces.

12.2.1 Tangible User Interfaces (TUIs)

One kind of NUIs that holds interesting potential in education are Tangible User Interfaces (TUIs). TUIs are systems in which users interact with digital information through the physical world. The most common implementation of a TUI is a horizontal interactive tabletop that detects the location and orientation of physical objects (tagged with fiducial markers, which are similar to QR codes), and displays additional information on top of them usually with a projector. They transform traditional manipulatives into dynamic objects that respond to users' actions through an augmented reality layer. Since anything can be displayed on the virtual layer, it allows designers to combine physical and digital affordances in a way that was not possible before. For example, the Reactable (Fig. 12.1, left) is an interactive tabletop created to support creativity through musical exploration. In this environment, each object is associated with a specific musical sound or action (e.g., changing the pitch or volume of a tone). Users can easily connect objects together to create musical compositions in an intuitive and playful way. Another example is the Sandscape system (Fig. 12.1, right), which allows users to design and understand landscapes using sand. The tangible interface then displays various information about the landscape model to show its height, slope, contours, shadows, drainage or other features of the simulation.

From a pure HCI (Human–Computer Interaction) perspective, there are several advantages associated with TUIs. They leverage everyday objects or material with which users are already familiar. This significantly reduces the amount of time necessary to learn the interface. When well designed, users can just jump in and

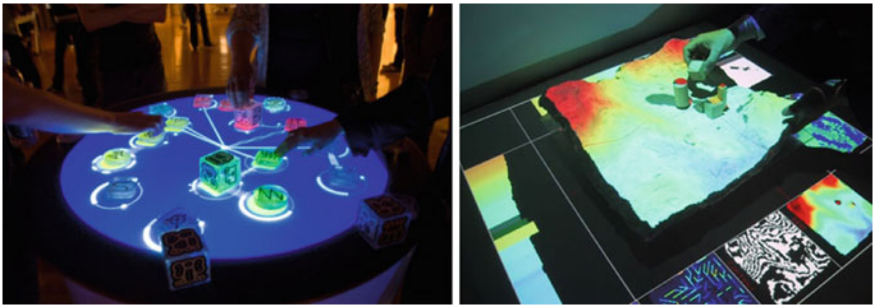

Fig. 12.1 On the *left*, an interactive tabletop for creating music (the Reactable). On the *right*, a landscape created with sand and augmented with a digital information (the Sandscape system)

explore the system on their own without any need for tutorials or explanations because the interface is intuitive and obvious to many users. TUIs also combine the best of the physical and digital world. 3D physical objects provide essential information to the users through their shape, weight, texture and colors, while the 2D digital layer can be used to display anything above and between the objects. Finally, TUIs facilitate bi-manual interactions: because of the tactile feedback, users naturally know in which orientation and configuration the objects lie in their hands. In comparison, touch interfaces require users to constantly check if they have selected a virtual item or if they are dragging it as intended Those advantages allow users to perform tasks more quickly and more accurately compared to touch interfaces (Tuddenham, Kirk, & Izadi, 2010).

12.2.2 TUIs in Education

Educational designers are generally enthusiastic about the potential of TUIs because manipulatives have been used for centuries to study how young children reason about the world (most notably by Piaget) and to progressively introduce them to abstract ideas. Friedrich Froebel (1782–1852), for instance, was a German teacher who created the concept of kindergarten. He designed a set of physical objects called "Froebel gifts" to help students learn about geometrical shapes and patterns. In one set, small cubes were used to introduce children to mathematical concepts such as addition, subtraction, multiplication and division. By explicitly integrating complex concepts into manipulatives, Froebel was among the first educators to design various sets of educational toys.

Later, Maria Montessori (1870–1952), an Italian educator, cleverly designed a different set of manipulatives to teach mathematical concepts in early childhood. For instance, she used golden beads to help children grasp the idea of large quantities and help them transition toward abstract numbers by associating stacks of beads with numbers (Fig. 12.2). Montessori programs are still alive, and it has been shown that children who were randomly selected to attend a Montessori program score higher on standardized math tests than children who had not been selected and attended a traditional program (Lillard & Else-Quest, 2006). Manipulatives have also been used to support learning of ratios, geometry, physics, and many other complex ideas in science. TUIs build on those successful applications, but they do not have to be limited to simple concepts such as addition or multiplication. Since the digital layer can represent anything, it is possible to design rich and complex learning scenarios that incorporate simulations, multiple external representations, dynamic scaffolding, just-in-time resources, and other mechanisms known to support learning. TUIs also support exploratory and expressive learning, they make learning activities more concrete, playful and engaging, they are well-suited to spatial domains, and have features that make them ideal for collaborative learning. Additional benefits of TUIs are summarized in Fig. 12.3 (reproduced from Marshall, 2007).

Considering the affordances of TUIs for learning, it is relatively surprising that there is not a wealth of educational environments leveraging this new technology. Many TUIs are created for artistic expression (e.g., the Reactable on the left side of Fig. 12.1) or for merely replacing elements of a traditional Graphical User Interface such as sliders, buttons or toggle switches (Schmidt et al., 2014). But there have been some attempts to design educational TUIs. For example, the Youtopia system (Fig. 12.4, left) allows young children to analyze the relationship between the economic development of communities and their available resources (renewable and non-renewable). Learners use physical tokens to "stamp" the landscape to modify it by building a facility, use resources or check their progress. A study found that assigning physical stamps to users supported more equitable verbal and physical participation compared to a control group where any player could use any stamp (Fan, Antle, Neustaedter, & Wise, 2014).

Another example is the TapaCarp system designed by Cuendet, Bumbacher, and Dillenbourg (2012; Fig. 12.4, right side). Apprentices in carpentry use physical

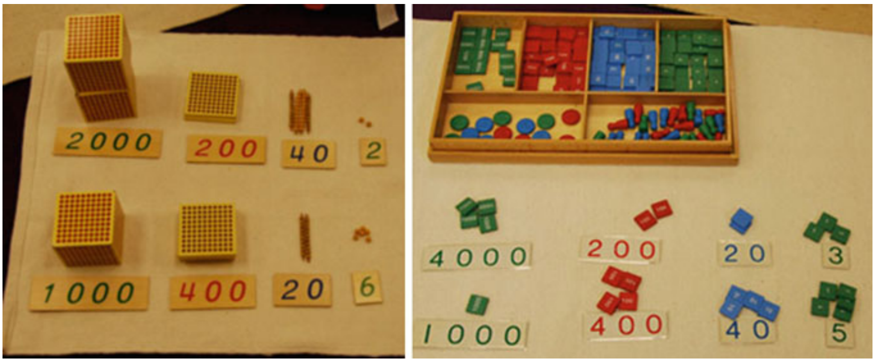

Fig. 12.2 On the *left*, golden beads used in Montessori schools. On the *right*, tiles used to facilitate the transition toward numbers

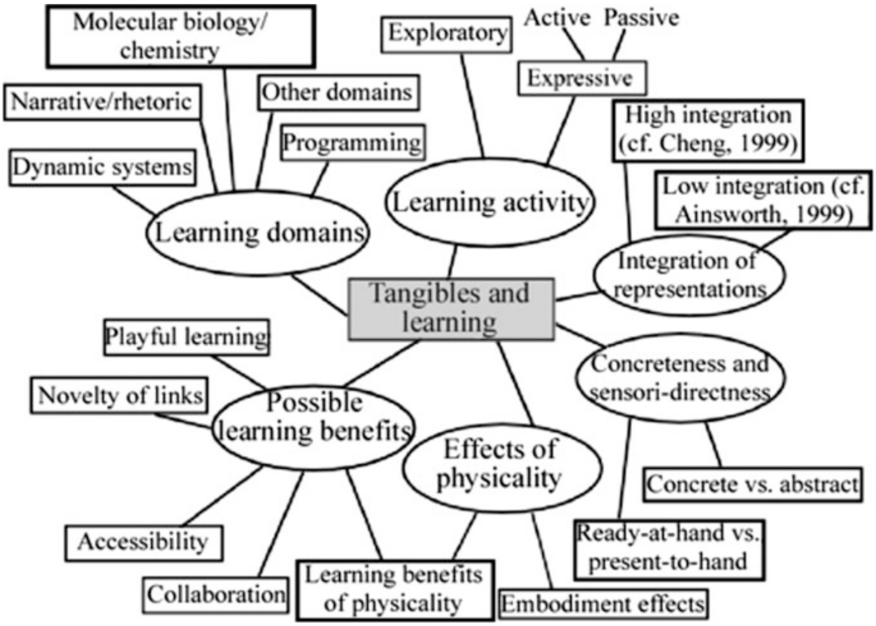

Fig. 12.3 An analytical framework that describe the potential benefits of tangible user interfaces (TUIs) in educational settings (Marshall, 2007)

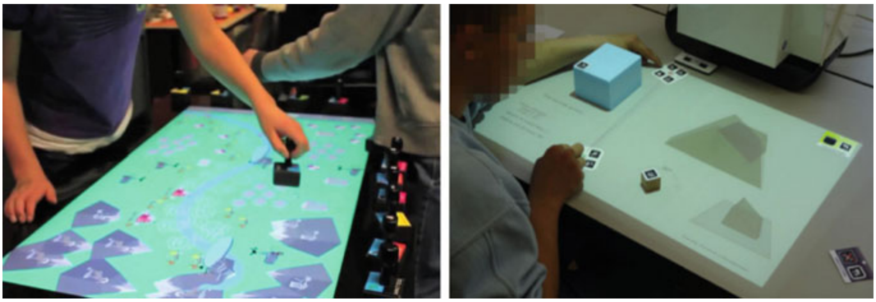

Fig. 12.4 Two examples of TUI in education. On the *left*, the TapaCarp environment allows apprentices in carpentry to train their spatial skills. On the *right*, the Youtopia system helps 5th graders to learn about sustainability in small groups

objects to understand orthographic projections displayed next to them. In one study, the authors found that tangibles helped students perform better compared to a virtual representation (it should be mentioned, however, that it did not significantly increase their learning gains). There are other examples of the benefits, and sometimes disadvantages, of TUIs for learning (e.g., Schneider, Jermann, Zufferey, & Dillenbourg, 2011). However, I will not describe them exhaustively here. Suffice to say that in some situations, tangible interfaces have affordances for learning that other interfaces do not have.

But what are the best ways to exploit the learning experiences that students have with TUIs? Below I introduce a framework that could answer this question, and provide designers with preliminary guidelines for integrating those new experiences with classroom instruction.

12.3 The “Preparing for Future Learning” (PFL) Framework

Even though the past decades have witnessed important technological innovations like NUIs, classrooms and online learning platforms still operate under the same principles that have existed for centuries. They favor a “tell-and-practice” (T&P) paradigm, where students are first exposed to a new idea, usually by a teacher giving lectures, and then given an opportunity to apply this new knowledge by solving exercises. Learning scientists (e.g., Bransford & Schwartz, 1999), however, have been criticizing this paradigm, showing that students gain a superficial mastery of the concepts taught. Instead, they argue that there is a “time for telling” (Schwartz & Bransford, 1998): “when telling occurs without readiness, the primary recourse for students is to treat the new information as ends to be memorized rather than as tools to help them perceive and think”. Our first instinct is to solve this issue is by doing *more* telling. Schwartz and Bransford argue that under these conditions, students often think that they perfectly understand a concept, when in fact, they are missing the point.

Making sure that students are ready to learn from standard instruction is at the core of some constructivist frameworks. One of them, in particular, is the Preparing for Future Learning framework (PFL; Bransford & Schwartz, 1999). The PFL framework recognizes that more often than not, students come to the lecture hall without the prior knowledge necessary to understand the lesson. This theory suggests that instead, we should design learning activities where students can build some prior knowledge, develop curiosity for the domain taught and think critically *before* they are being told what the concept, formula or solution is. The PFL framework was originally developed to target one specific kind of prior knowledge: perceptual differentiation. The main methodology used to achieve this goal are *contrasting cases*. Contrasting cases are carefully designed representations of a concept, where some representations vary in terms of their *surface features* (superficial details that are unimportant) and their *deep features* (variables that are central to the concept taught). Students’ goal is to analyze those cases to separate surface features and deep features. This way, when they are listening to a lecture or reading a textbook, they have a more refined understanding of which information to focus on (the deep features of a concept) and what to ignore (the surface features). This relates to the concept of authenticity discussed in Jacobson’s chapter.

In various studies, researchers have found the PFL framework to yield positive results on students' learning. Schwartz, Chase, Oppezzo, and Chin (2011), for instance, taught adolescents about density using a set of contrasting cases (CCs) featuring buses of various sizes filled with clowns. The surface features were the types of clowns and buses. The deep features were the number of clowns and the size of the buses. Two experimental groups did the same activity, but in different orders. The T&P ("tell and practice") group was told the formula for density and then asked to practice this formula on the CCs. The constructivist group invented a formula for density using the CCs first, and were formally taught about density afterward. The authors found that even though both groups did equally well on standard word problems, the second group transferred the idea of density to semantically unrelated topics much more *frequently*. In a different study, Schwartz and Martin (2004) showed similar results where students in statistics had to create a reliability index for baseball pitching machines—in other words, they had to invent the formula for the concept of standard deviation from a set of CCs. They found that students in the PFL condition did better on a test that included additional learning resources compared to students who followed a T&P instruction.

In the next section, I explore how TUIs could be used as a preparation for future learning. While CCs focus on having students perceive details that they might otherwise miss, I suggest that TUIs have particular affordances that could also be used in a PFL fashion.

12.3.1 Tangible User Interfaces as a Preparation for Future Learning

This section describes learning environments that I have designed and/or evaluated in collaboration with others using cutting-edge technology for building mixed-reality interfaces (Fig. 12.5). This preliminary design cycle has explored domains as varied as neuroscience, math and probability, neuro-acoustics and logistics. In those examples, students learn about a complex system or a scientific phenomenon in a constructionist fashion by re-*constructing, de-constructing* or *re-assembling* its physical elements. The augmented reality layer displays digital information based on students' actions. For instance, it can project a simulation, a connection between two pieces, additional information or display hints. This kind of learning environment allows the system to dynamically adapt to users' actions and provide (to some extent) personalized learning experiences. This type of "just in time" feedback is especially useful for scaffolding students' learning. Figure 12.5 describes four TUIs designed for educational purposes.

On the top left of Fig. 12.5, the Brain Explorer system (Schneider et al., 2013) allows students to learn about concepts in neuroscience by interacting with a small-scale brain. They first take apart the physical brain regions, and the augmented reality layer displays visual pathways between the tangibles. Students can

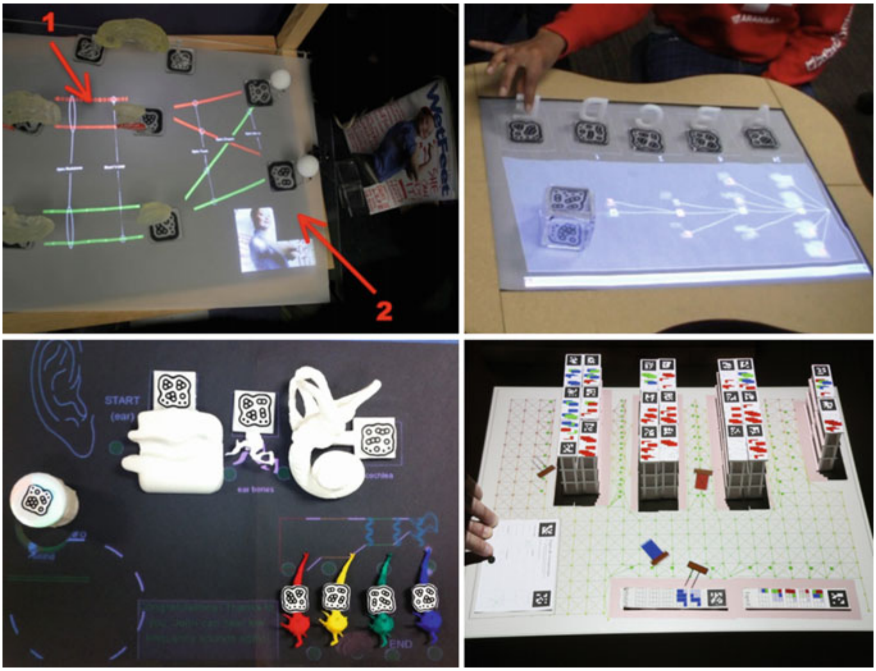

Fig. 12.5 Four examples of tangible interfaces in education: Brain Explorer (*top left*), Combinatorix (*top right*), Ear Explorer (*bottom left*) and the Tinker Table (*bottom right*)

then disrupt those pathways using an infra-red pen (arrow #1 on the picture), and the system displays the impact of those lesions on the visual field of this brain (arrow #2 on the picture). In this example, Mayer's loop is disrupted on the left side of the brain, which means that this subject loses the top right quadrant of his visual field. By repetitively iterating through different scenarios, students can start to build a basic understanding of how the brain separates visual information into four quadrants.

On the top right corner of Fig. 12.5, the Combinatorix system allows students to explore basics concepts in probability. By recombining the letters A, B, C, D and E, they build an intuitive understanding of how many combinations can be formed with those letters through the various visualizations that are displayed above them (e.g., a probability tree). The system then offers additional challenges, where various constraints are added. For instance, how many letters can be formed when E has to be the second letter in the sequence? Or how many letters can be formed when A has to be before B? By progressing through the various challenges and by analyzing the visualization displayed above the tangibles, students start to build an intuition about how the different formulas in combinatorics are structured.

On the bottom right corner of Fig. 12.5, The Ear Explorer interface allows students to rebuild the human hearing system from scratch. The goal is to recreate the pathway between the outer ear and the auditory cortex by connecting 3D-printed replicas of the organs of the hearing system. Students can then generate sound waves at different frequencies to test their construction and see which waves reach the brain. An important feature of the interface is the ability of students to make mistakes and build dysfunctional structures. They can then correct those errors by using the information box (i.e., the circle on the bottom left corner) where they place tangible items to access hints and can learn additional information about each organ.

Finally, on the bottom right corner of Fig. 12.5, the Tinker Table is a tangible interface for apprentices in logistics. Students learn about good design principles for organizing a warehouse by building a small-scale model, that they then analyze using more abstract representations such as graphs. This allows the teacher to provide concrete examples of interesting pedagogical situations, and to progressively move toward more formalized representations of warehouses' efficiency (e.g., equations).

This first wave of systems provided enthusiastic feedback from user and promising directions to follow. We learned one main lesson from building and testing those systems: using them as a stand-alone learning activity—where would students to learn everything about a phenomenon—is an extremely challenging task. We realized that using those systems for mastery learning was potentially misguided, and prevented us from using TUIs to their full potential. Instead, we observed that students were more likely to be intellectually and emotionally engaged about the underlying mechanisms of a phenomenon when interacting with a TUI. They became more curious, started to ask critical questions and engaged their peers into conceptual discussions. Those behaviors are important in their own rights, because they can also prepare students for future learning.

The main design guideline for those activities was to target the situation (mentioned by Bransford and Schwartz above) where over-telling students pushes them to "think that they know" because they have memorized information from a lecture when, in fact, they have large gaps in their knowledge. The learning activities on the TUI have the main function of helping students explore the domain taught and realize that there are subtle points that are more difficult to understand than expected. One side-effect of this intervention is to raise their curiosity: we also expect them to have more questions about the topic taught after having interacted with the TUI.

12.3.2 Empirical Findings

A series of controlled experiments combined the PFL framework with some of the TUIs shown in Fig. 12.5. The experimental design was a replication from Schwartz et al. (2011). College-level students interacted with a TUI either *before* or *after* following a standard kind of instruction (i.e., reading a textbook chapter or watching a video lecture).

In a first study (Schneider et al., 2013), we found that individuals who used Brain Explorer before reading an excerpt of a textbook outperformed students who used the TUI after reading the text on a learning test (Fig. 12.6, top left). Those results suggest that TUIs can be used to prepare students for future learning, and that using this kind of interface in a T&P kind of instruction is less effective. Additionally, we found differences in the quality of students' elaborations when thinking aloud. Students in the PFL group made more high-level comments (such as defining a rule based on a set of observations), which suggests that they tried to formulate their mini-theory of how the brain processed visual information. In the T&P condition, students made more simple observations (such as describing the effect of one lesion on the visual field of the brain) and repeating information from

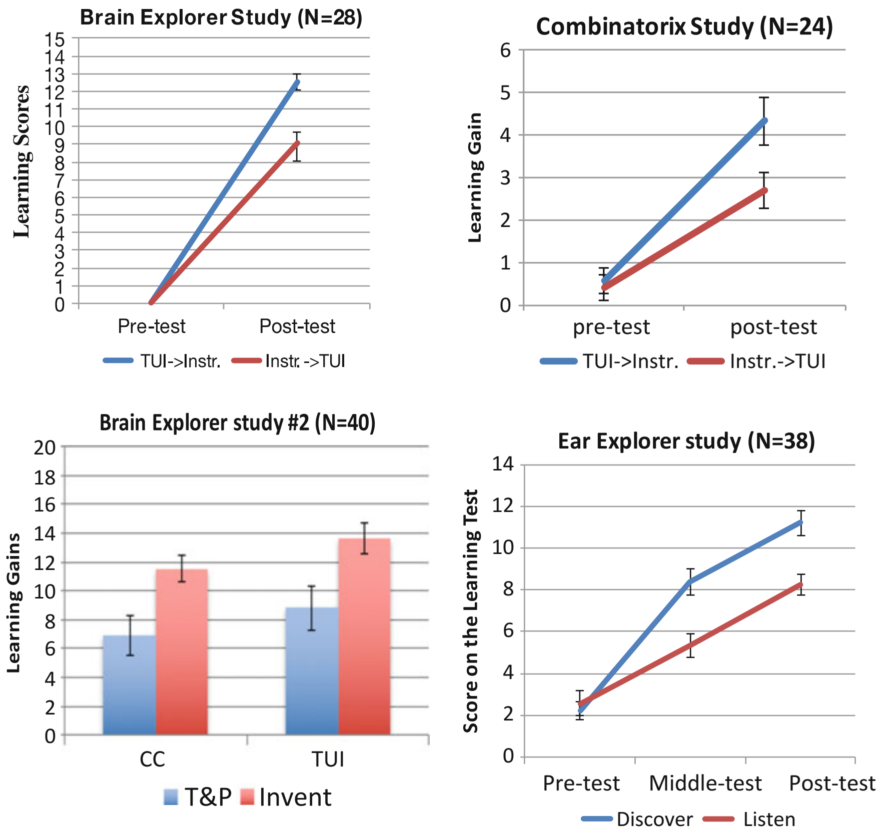

Fig. 12.6 Results of the 4 empirical studies where the PFL framework was applied to TUIs. The top figures compared the "tell and practice" paradigm (*red line*, also labelled as "Instruction → TUI") with the PFL sequence ("TUI → Instruction"). The *bottom left* graph replicates those results and compares TUIs with a set of Contrasting Cases (CC). The *bottom right* graph compares two PFL sequences and asks students to freely rebuild a complex system (discover) or follow step by step instructions (listen)

the text. Overall, we found that the quality of students' elaborations was a significant mediator for their learning gains. It suggests that the PFL sequence increased learning gains by having students construct their own mental model of the inner workings of the human brain—which they could then use to make sense of the text. Based on Bransford and Schwartz (1999)'s framework, we hypothesize that students in the T&P did not feel the same need to construct their own mini-theory: they likely believed that they knew how the brain worked, because they had the chance to memorize this information from the text. In other words, the text might have made them overconfident in their ability to understand the inner workings of the human brain.

In a second study (Schneider & Blikstein, 2015a, b, c), we replicated those results in a different domain (probability) using a pre-recorded video lecture where dyads of students interacted with the Combinatorix system (Fig. 12.5, top right). Again, students in the PFL condition outperformed students in the "tell and practice" group (Fig. 12.6, top right) on the learning test. We found that students in the PFL group explored the interface to a greater extent (e.g., they did more actions and accessed the visualizations more often) and spent more time discussing the concepts taught. On the other hand, students in the "tell & practice" group spent more time trying to remember information, such as formulas from the video lecture. This suggests that the T&P sequence pushed students to memorize, recall and apply information—at the cost of having in-depth conceptual discussions.

In the third study (Schneider & Blikstein, 2015a, b, c), we used a 2×2 experimental design to replicate those findings and compared the TUI (an updated version of Brain Explorer) with a set of Contrasting Cases (CC). CC are state of the art discovery learning activities, which is what was used in the PFL studies mentioned above. Additionally, we included two questionnaires between the activities. One questionnaire captured students' curiosity by asking them to write all the questions that they would like to see answered about the human visual system after the first activity. A second questionnaire measured the quality of their mental model by asking them to draw a diagram that summarized everything that they had learned so far. Again, we found that the students in the PFL condition outperformed students in the "tell and practice" group on a pre/post questionnaire measuring their learning gains. We also found that students who first interacted with the TUI built more complex mental models (as shown by the drawings they made between the two activities; see examples on Fig. 12.7) which was significantly correlated with their learning gains. They also became more curious (as expressed by the number of questions they asked themselves half-way through the study), which was significantly correlated with the quality of their mental model. This shows how the PFL sequence increased students' curiosity, which had a positive impact on the quality of their mental models. Better mental models, in turn, were associated with higher learning gains.

We also observed that learning gains were higher compared to a state of the art discovery-learning activity (Contrasting Cases). This does not mean that TUIs are better than CC for preparing students for future learning: it only means that for this specific domain, this specific TUI and CC, the interactive system yielded higher

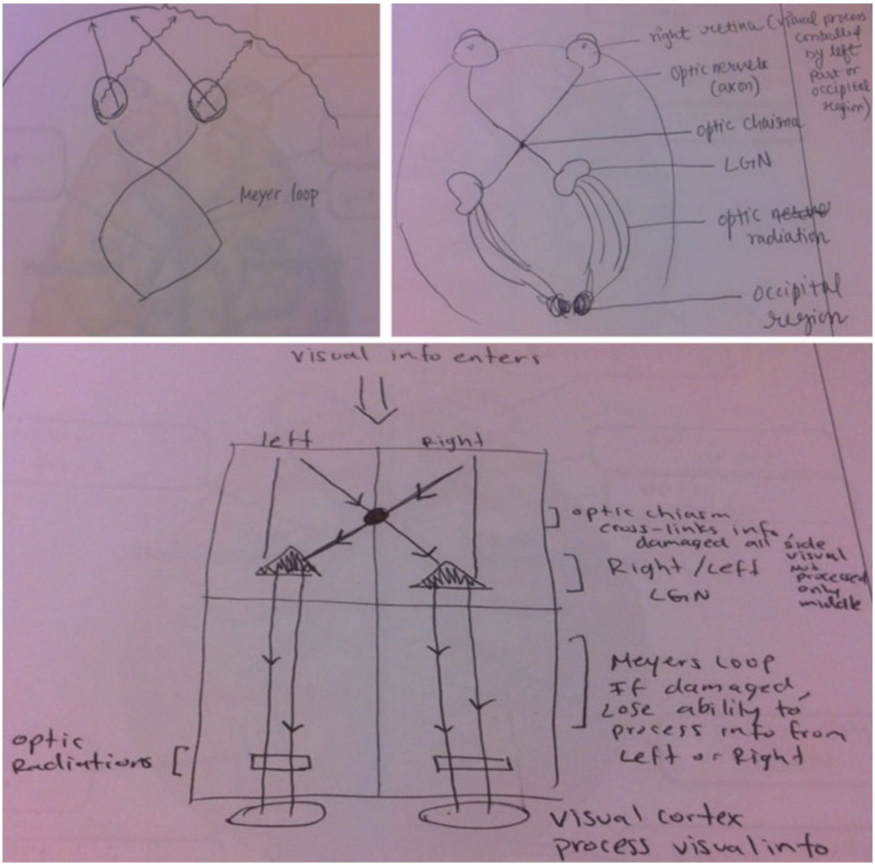

Fig. 12.7 Three categories of models drawn by the participants of study 3. The model on the *top left* has no or little useful information; the one on the *top right* has some useful information, mostly about the terminology; and the one on the *bottom* contains clear signs of conceptual understanding. Students in the PFL condition drew models that were more similar to the last two, while students in the T&P condition were more likely to draw models similar to the first two

learning gains for those students. This might be caused by a variety of factors: a higher engagement due to the novelty of the interface, the fact that complex systems might be a particularly good fit for TUIs, or because it is easier to collaborate around physical objects than a sheet of paper. Exploring this difference should be the focus of additional studies.

Finally, a last experiment (Schneider et al., 2015) refined the experimental design and clarified this difference. More specifically, we wondered if this effect was merely caused by the fact that students in the PFL sequence started the activity by physically rebuilding a system, which might have increased their engagement and carried over to the second activity. Similarly, it is possible that completing the standard instruction in the T&P sequence bored the participants and contaminated the second activity (i.e., when they interacted with the TUI). In summary, are the increased learning gains merely caused by a motivational effect? To answer this question, we used the Ear Explorer system (Fig. 12.5, bottom right) and asked dyads of students to rebuild the human hearing system from scratch. In one condition, they did so freely. In a different condition, a video of a teacher was displayed on the bottom right corner of the table, explaining the steps to follow to rebuild the system. Both groups then read an excerpt from a textbook which described how the human hearing system works. We found that students in the first group scored higher on a learning test, as shown on the fourth graph of Fig. 12.6 (bottom right). They also accessed the information box more often, which was significantly correlated with learning gains. It suggests that, when given the chance, students who could freely discover a domain were more likely to take advantage of additional resources. Finally, those results demonstrate that combining the PFL framework with TUIs is not about a quick boost in engagement that carries over the standard instruction: it is about having students actively build mental models of a concept, so that they can then use this prior knowledge to make sense of a lecture or textbook chapter.

In summary, those four studies provide evidence that using TUIs in a PFL fashion can significantly increase learning gains compared to a traditional T&P approach. More specifically, there are evidences that students in the PFL group were more likely to take advantage of the TUI, became more curious, made higher-level reflections, had more conceptual conversations and were able to build more complex mental models. In comparison, students in the T&P were more likely to spend their time recalling and applying information from a standard instruction (e.g., when watching a video lecture or reading a textbook chapter) and might have been overconfident in their ability to understand the concepts taught.

12.4 Preliminary Design Principles

Even though more research is needed to explore the effect described above, I suggest here a few preliminary design guidelines for creating technology-enhanced PFL activities. Those guidelines are based on my experience designing and evaluating those systems, and thus are not always supported by empirical findings.

1) **Target prior knowledge**: As mentioned above, the best use of Tangible Interfaces might not be to directly teach concepts to students, but to prepare them for future learning. The activity should be designed to help students build some prior knowledge, raise their curiosity, push them to ask critical questions and highlight potential misconceptions so that they can ground a teacher's explanations into a concrete, accessible experience—and not just refer to an abstract, formalized representation of the concept taught (i.e., equations or rules).

2) **When dealing with complex systems**: The studies above suggest that having students either physically deconstruct, reconstruct or recombine elements of a complex system is a potentially useful way to prepare them for future learning. It allows them to build a mini-theory of a concept as they are physically interacting with its different parts. Gardner's chapter provides some examples of this.
3) **Design coherent mappings to physical objects**: When designing a tangible system, a crucial decision is to choose what the physical objects will represent. Ideally, the tangibles should (1) make intuitive sense to the learners (for instance, it is clear what a brain represents; but it is less clear which idea a cube is supposed to embody), (2) activate their prior knowledge (e.g., we found that the shelves of the Tinker Table helped apprentices in logistics activate knowledge from their everyday workplace), (3) be central to the activity to support students' learning (e.g., by helping them explore a domain by quickly trying out combinations), and (4) propose synergies between the physical and digital layer (e.g., each representation should help the learners make sense of the other representation: a physical configuration should help students understand a simulation or a graph projected on the augmented reality layer). For more on this topic, the interested reader should feel free to consult Mina Johnson's chapter in this book.
4) **Foster curiosity and engagement**: Virtually all learning theories recognize that engagement is a necessary pre-requisite for learning. When designed well, tangible interfaces provide students with engaging ways to think about hard concepts in STEM, because they can represent and embody those ideas in a playful way (Marshall, 2007). This should be a central aspect to be kept in mind when designing an educational TUI.
5) **Making learning social**: Another advantage of TUIs is that they support collaborative learning in small groups, by making it easy to own and share physical objects. Social learning has been recognized as one of the most powerful ways to foster constructivist learning in the learning sciences and can be supported in tangible environments, as discussed in Kraemer's chapter Interactive tabletops, because of their size and shape, are natural environment for multiple users. It's a shared workspace where students are fully aware of each other's actions, which helps them externalize and share their thinking process. In a similar way, it serves as a "group working memory" where the set of objects represents the current state of the problem. Finally, collaboration can be facilitated by assigning roles (Schneider & Blikstein, 2015a, b, c) or tangibles (e.g., Fan, Antle, Neustaedter, & Wise, 2014) to students, which promotes engagement and participation from each member of the group. For a more exhaustive description of the benefits of interactive tabletops for collaborative learning, the interested reader can consult the review by Dillenbourg and Evans (2011).

12.5 Discussion and Conclusion

In this chapter, I have suggested that mixed-reality interfaces allow us to design new immersive learning experiences for teaching complex concepts in STEM. I have also described a framework in the learning sciences, called Preparing for Future Learning (PFL), which suggests ways to leverage those new learning experiences to enhance standard instruction. More specifically, empirical results show that having students reconstruct, deconstruct or reassemble a complex system on a TUI can have a positive impact on their learning, when this activity was used *before* a standard instruction (compared to a traditional T&P sequence).

Study 1 showed that neuroscience is a domain that could be particularly well-suited to a tangible implementation. When students used BrainExplorer in a PFL fashion, they were more likely to elaborate their own theory of the inner workings of the brain. In study 2, students who followed a T&P sequence tended to adopt a mechanistic behavior typical of classroom environments: they spent most of their time trying to memorize, recall and apply information from the lecture. They were also less likely to take advantage of the scaffoldings offered by the TUI. In study 3, there was evidence that students became more curious and built more complex mental models in the PFL sequence, and that the quality of their model was predictive of their learning gains. This really emphasizes the importance of helping students build prior knowledge that could be leveraged to understand standard instruction. The study also suggests that TUIs can be as good—or sometimes better—than state of the art PFL activities (i.e., Contrasting Cases). Finally, a fourth study clarified this effect. It showed that students did not learn merely because they could be physically active, or because of a novelty effect of the TUI: it showed that students who can actively build knowledge (via trial and errors, building hypotheses, testing them, and by freely exploring a domain) tended to learn more compared to the exact same activity where they are being told how things work. Additional studies should further refine this effect to design specific design guidelines for creating learning experiences that could be used in a PFL fashion.

In summary, the PFL sequence seemed to be helpful to students because it helped them become more curious. Their curiosity, in turn, supported constructivist learning. It became easier for them to create complex mental models that they could use to make sense of a standard instruction. The T&P sequence, on the other hand, seemed to promote a more mechanistic behavior: students tended to memorize and recall information, and they spent less time having conceptual reflections.

Those findings can be somewhat counter-intuitive because students and teacher tend to believe that the T&P sequence is usually more efficient. During informal interviews of study 1, students in the PFL group strongly believed that being instructed first would have helped them do a better job. Being immersed in an environment where they had to make mistakes and figure things out felt uncomfortable to them compared to the familiar T&P sequence. But the data shows that their intuition was wrong: they actually learned more by following a PFL progression. Additionally, when discussing with teachers during the Tinker Table project, they expressed reluctance to let students follow a PFL approach. For them, they had to teach students what they needed to know first. They did not feel comfortable letting students explore ideas on their own without being told what to do. Those observations reflect some deeply ingrained cultural beliefs about what counts as effective instruction.

Finally, there are a few obvious limitations that need to be mentioned. First, the activities described in this chapter were used to introduce students to concepts that were new to them. It is possible that the results would be different for students who already hold misconceptions about the concepts taught. Second, we found TUIs to be well-suited to spatial domains. It would likely be much more challenging to teach purely abstract concepts using tangibles. Third, the interventions were relatively short (20–30 min. for each activity). It is unclear if the findings above would hold for longer lessons. Finally, each study was conducted as a controlled experiment, which does not take the complexity of a classroom into account. Future work should study how this effect can be transferred to formal and informal learning environments.

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References

Bransford, J. D., & Schwartz, D. L. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education, 24*(1), 61–100.

Cuendet, S., Bumbacher, E., & Dillenbourg, P. (2012, October). Tangible vs. virtual representations: When tangibles benefit the training of spatial skills. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design* (pp. 99–108). ACM.

Dillenbourg, P., & Evans, M. (2011). Interactive tabletops in education. *International Journal of Computer-Supported Collaborative Learning, 6*(4), 491–514.

Fan, M., Antle, A. N., Neustaedter, C., & Wise, A. F. (2014). Exploring how a co-dependent tangible tool design supports collaboration in a tabletop activity. *Paper presented at the International Conference on Supporting Groupwork*, Sanibel Island, FL.

Lillard, A., & Else-Quest, N. (2006). The early years: Evaluating Montessori education. *Science, 313*(5795), 1893–1894.

Marshall, P. (2007). Do tangible interfaces enhance learning? In *Proceedings of the 1st international conference on Tangible and embedded interaction* (pp. 163–170). Baton Rouge, Louisiana: ACM.

Schmidt, D., Ramakers, R., Pedersen, E. W., Jasper, J., Köhler, S., Pohl, A., Baudisch, P. (2014). Kickables: Tangibles for Feet. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, (pp. 3143–3152). New York, NY, USA: ACM.

Schneider, B., & Blikstein, P. (2015). Flipping the lipped classroom: A study of the effectiveness of video lectures versus constructivist exploration using tangible user interfaces. *IEEE Transactions on Learning Technologies*, *9*(1), 5–17.
Schneider, B., & Blikstein, P. (2015a). Unraveling students' interaction around a tangible interface using multimodal learning analytics. *International Journal of Educational Data Mining, 7*(3), 89–116.
Schneider, B., & Blikstein, P. (2015b). Flipping the flipped classroom: A study of the effectiveness of video lectures versus constructivist exploration using tangible user interfaces. *IEEE Transactions on Learning Technologies, 9*(1), 5–17.
Schneider, B., & Blikstein, P. (2015c). Comparing the benefits of a tangible user interface and contrasting cases as a preparation for future learning. In *Proceedings of the 11th International Conference on Computer Supported Collaborative Learning—Volume 1* (pp. 134–141). International Society of the Learning Sciences.
Schneider, B., Jermann, P., Zufferey, G., & Dillenbourg, P. (2011). Benefits of a tangible interface for collaborative learning and interaction. *Learning Technologies, IEEE Transactions on, 4*(3), 222–232.
Schneider B., Wallace J., Pea, R. & Blikstein P. (2013). Preparing for future learning with a tangible user interface: the case of Neuroscience. *IEEE Transactions on Learning Technologies*, *6*(2), 117–129.
Schwartz, D. L., & Bransford, J. D. (1998). A time for telling. *Cognition & Instruction, 16,* 475–522.
Schwartz, D. L., Chase, C. C., Oppezzo, M. A., & Chin, D. B. (2011). Practicing versus inventing with contrasting cases: The effects of telling first on learning and transfer. *Journal of Educational Psychology, 103*(4), 759–775.
Schwartz, D. L., & Martin, T. (2004). Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction. *C&I, 22*(2), 129–184.
Tuddenham, P., Kirk, D., & Izadi, S. (2010). Graspables revisited: Multi-touch vs. tangible input for tabletop displays in acquisition and manipulation tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2223–2232). New York, NY, USA: ACM.
Wigdor, D., & Wixon, D. (2011). *Brave NUI world: designing natural user interfaces for touch and gesture*. Elsevier.

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