Discovery Versus Direct Instruction: Learning Outcomes of Two Pedagogical Models Using Tangible Interfaces

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Abstract: We investigate the effect of using a tangible user interface (TUI) for discovery-based learning. For this purpose, we built EarExplorer, an interactive tangible system where students can manipulate and connect parts of the auditory system to rebuild a functional structure. An augmented reality layer displays sound waves and shows how they are transformed at various stages of the process. Our previous work suggests that TUIs are particularly good at preparing students for future learning; that is, students learn more when they can explore a novel domain with a TUI before compared to after receiving a traditional (e.g. lecture or text based) instruction. In this study, we isolated the impact of structured guidance versus no guidance during a hands-on TUI activity on learning. In one condition, students rebuilt the hearing system by self-driven discovery; in another condition they rebuilt it by following the step-by-step instructions of a video-teacher. We found that the first group ("discover") significantly outperformed the second group ("listen") by ~27% on the final learning test. To explain those results, we analyzed the TUI logs and explored how this effect unfolded with participants of different ability (i.e., low versus high GPA students).

Keywords: tangible user interface; collaborative learning; tabletop

Introduction

The recent decades have seen the development of a wide range of pedagogies based on constructivist learning theories that are often pitted against more traditional pedagogies (Piaget, 1998; Papert, 1980). They range from experiential and project-based learning methods to inquiry- and discovery-based approaches (Jong & Joolingen, 1998). However, there is an ongoing debate about the effectiveness and value of these approaches, compared to more structured and guided instructional methods (Kirschner, Sweller and Clark, 2006). In this paper, we argue that the effectiveness of the various learning methods strongly depends on the context in which they are used; in particular, we believe that certain technologically-enhanced learning environments are particularly well suited for constructivist-based approaches compared to more traditional instruction. In line with this belief, researchers have been advocating for new computational technologies as means for constructivist-based learning activities: when properly designed, new materials such as robotics, physical computing and tangible user interfaces (Papert, 1980; Blikstein, 2013) can be powerful building blocks in enriching such activities and facilitating their implementation in classrooms. Specifically, we are interested in exploring the potential of technologically enhanced hands-on activities for discovery learning. We build our work on the assumption that Tangible User Interfaces (TUIs) provide an ideal framework for using discovery-based learning activities as introduction for learners to a wide range of concepts: they form a highly controllable design space for interaction designers while providing all tools necessary for the creation of microworlds that enable intuitive interactions, physical manipulations and at the same time encompass rich information layers through augmented-reality techniques.

The main contribution of this work is to propose that augmented-reality-based TUIs are effective environments for discovery learning activities. In our study, participants engaged in a learning activity about the human hearing system on a newly designed TUI. One group used a discovery-based approach with minimal guidance, while the other group received video-based guidance throughout the activity. Our findings suggest that the discovery group seemed to gain more from the learning activity than their counterpart.

Theoretical framework: Preparing for future learning (PFL)

One of the main claims of constructivist approaches to learning is that students should explore or discover a given phenomenon before being told the normative explanation (Piaget, 1998; Bransford & Schwartz, 1999). The constructionist movement further stresses the importance of building, interacting with, and sharing constructed artifacts (Papert, 1980), as this provides opportunities for debugging one's own understanding by confronting in-progress theories with real-world feedback. The idea is to empower students by making them the agents of their learning process: their task is to actively construct knowledge by using their intuition and prior knowledge, build artifacts, and refine their micro-theories as they observe the performance of these artifacts in

the world. As such, students need to generate hypotheses, test them by gathering data, and construct a theory based on their observations. This process, as argued, could deepen students' conceptual understanding of a phenomenon (Bransford & Schwartz, 1999), as opposed to rote memorization of terminologies and procedures.

However, constructivist learning methods such as discovery learning are difficult to develop and implement in real-world classrooms. deJong and van Joolingen (1998) highlight three problems that students encounter in discovery learning: first, novices usually find it difficult to formulate a testable hypothesis with the data at hand; they tend to stick to their first hypothesis despite conflicting evidence. Second, designing a clean experiment to confirm or disconfirm a hypothesis is a difficult task, even for experts; this process becomes harder when the hypothesis is not clearly formulated. Third, finding patterns in the data beyond simple relationships is a skill that most novice students do not have. Combined with the lack of adequate teacher preparation, good assessment rubrics, and support materials, discovery learning is rarely used in classrooms in a sustainable way. Oftentimes, in the process of adapting discovery- or inquiry-based learning activities for the classroom, even progressive teachers fall back to more structured, less "authentic" approaches that overly simplify the activities (Chinn & Malhotra, 2002).

One theory that tackles those issues is the "Preparing for Future Learning" (PFL) framework (Bransford & Schwartz, 1999). This framework postulates that students do not necessarily have to discover the principles at hand during the discovery task. What matters is that they develop experiences and refined perceptions of the deep features of a phenomenon and develop their own corresponding theory. In their work, Bransford & Schwarz (1999) have students engage in activities on comparing contrasting cases (i.e. cases whose difference highlight core aspects of a phenomenon at hand); they then compare their own micro-theories with the accepted view of a concept. In our work, instead of constructing contrasting cases, we propose a well-designed discovery activity that serves the purpose of preparing students for future learning. More specifically, we are interested in using TUIs that incorporate physical and realistic items as interaction objects to introduce students to a new domain; additionally, we want to show that students will learn more from a lecture following the activity than a group that is guided through the task on the tangible interface.

Previous work and rationale of the current study

For the scope of this paper, we are interested in pursuing work started with another TUI developed in our lab about the role of TUIs as media that foster PFL. BrainExplorer (Fig. 1; Schneider, Wallace, Blikstein & Pea, 2013) is an interactive tabletop where users can explore the way the human brain processes visual information. Students take apart a physical replica of a brain while an augmented reality system displays visual pathways between brain regions. Users can then use an infrared pen to create lesions and observe the impact of their actions on the visual field of the subject. In a controlled experiment, we showed that students who first used BrainExplorer and then read a textbook chapter outperformed students who completed the same activities but in the reverse order (Fig. 1, right side). Our conclusions were that TUIs support students' elaboration of their own micro-theories and create an engaging point of entry for exploring a domain (Schneider, Jermann, Zufferey & Dillenbourg, 2011).

It is possible that starting with a hands-on activity in general is the one thing that caused higher learning gains in the previous study: as students were complete novices in the domain of the task, engaging with the TUI first gave students the opportunity to gain some initial experiences on which they could build on when receiving the formal instruction. However, we believe that the nature of the hands-on task itself had an impact on students' conceptual learning. For the current study, we manipulated the level of guidance students received in an explorative task on a similar TUI. The goal was to isolate the effect of self-driven discovery versus guided exploration on learning. The TUI was about the functioning of the human hearing system, a topic that was novel to the participants. Two groups started out with the TUI before receiving a text instruction on the topic; one group watched a video of a teacher explaining the function of each organ and how to connect them in the TUI. The other group rebuilt the hearing system without guidance. It is crucial to note the role of the activity design in the TUI: The activity was designed in such way that it provided the required range of various actions to allow for self-driven exploration, yet it was constraint enough to prevent participants to be overwhelmed with the breadth of possible actions or get off-track and focus on irrelevant aspects of the system. For instance, students only had to deal with eight tangibles, which allowed them to focus on the core mechanisms of the human hearing system; furthermore, additional information was only available on-demand through the information box. This is important as research shows that very loosely structured tasks that provide too many possibilities of manipulations are detrimental for novice students and can actually hamper their learning as they do not know what aspects to focus on, and how to make sense of the task at hand (Kirschner, Sweller and Clark, 2006). Within such a context, we hypothesize that the discovery group will be better prepared to learn from the text compared to the group that received a highly-scaffolded guidance during the hands-on task.
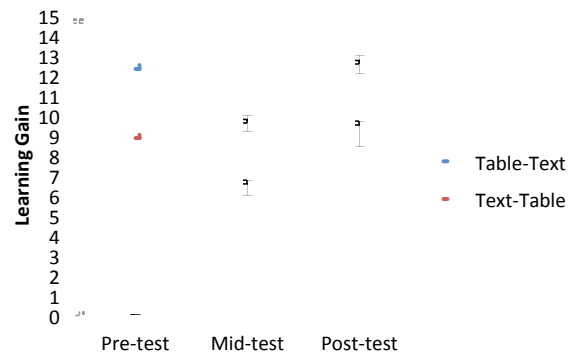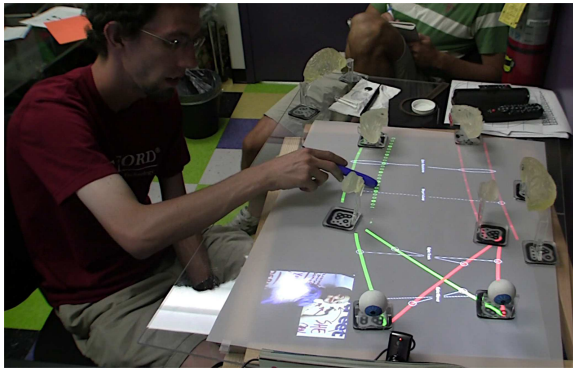
Figure 1. The BrainExplorer system. A user cut Mayer's loop and is reflecting on the effect of this lesion on the perceived visual field (on the bottom right corner)

EarExplorer

Design requirements

When designing EarExplorer, we started with the constraint of teaching a phenomenon that entails complex abstract concepts, yet is embedded in a highly spatial domain where one could take advantage of the "3Dness" of physical objects. These requirements are met by the human auditory system: it represents a system that transforms auditory information across various stages through a set of interconnected organs. Pilot interviews of novices who read a text about the hearing system revealed that students had trouble visualizing the different transductions happening in the ear (i.e. sound waves vibrate the ear drum with various sound pressures; the ear drum then moves the maleus to pass information as a mechanical movement; the ear bones then move the liquid contained in the cochlea and activate particular segments of the basilar membrane rolled in the cochlea). Novices also struggled with the spatial mapping of different sound frequencies on the basilar membrane. High frequencies carry more energy and vibrate thicker segments at the beginning of the membrane, while low frequency sounds traverse the membrane until it finds a segment thin enough to be activated. This mapping is counter-intuitive for novices, because we usually represent sounds on a number line from low (left) to high (right) frequency. Thus, the design of our first prototype focused on those two aspects: the propagation and transduction of sounds through the hearing system, and the spatial mapping of sound frequencies on the basilar membrane.

Design of the system

EarExplorer consists of a tabletop interface with 3D-printed tangibles tagged with fiducial markers. A projector displays an augmented reality layer by reflecting its image on a mirror held above the tabletop. A camera is attached to the mirror and detects the location of the fiducials on the tangibles (Figure 2). The starting screen displays three elements: the outer ear, which is the starting point of the activity (top left corner, Fig. 2); the auditory cortex, which is the end point of the activity (bottom right corner, Fig. 2); and an information box (bottom left corner, Fig. 2). Eight tangibles are arranged around the projected area. Students are asked to connect the tangibles between the starting point and the ending point to let sound waves reach the auditory cortex. Each tangible can be positioned in the information box at any time of the activity to display additional information about each organ. Users can use those hints to infer the correct sequence of tangibles and learn more facts about the function of each organ. The 8 tangibles (in bold below) serve the following functions:

1. The **speaker** generates sound waves at four different frequencies (low, medium, high, very high). Those four frequencies are displayed on top of the speaker with a specific color coding (from low to high frequency: blue, green, yellow, red). By flipping the speaker, users can generate a series of sound waves to test their system.

2. The **ear canal** then needs to be linked to the starting point of the activity (the outer ear) and carries sound waves to the eardrum. There are two feedbacks showing that the tangibles are successfully connected: first, students see the sound waves follow the ear canal; second, they also see the eardrum move back and forth in the augmented reality view as the sound waves reach the end of the ear canal.

3. The **ear bones** need to be connected to the ear canal. As the eardrum vibrates back and forth, the ear bones will provide a similar feedback: the augmented reality view will project the shape of the ear

bones on the tangible and animate them back and forth as the sound waves are reaching this part of the auditory circuit.
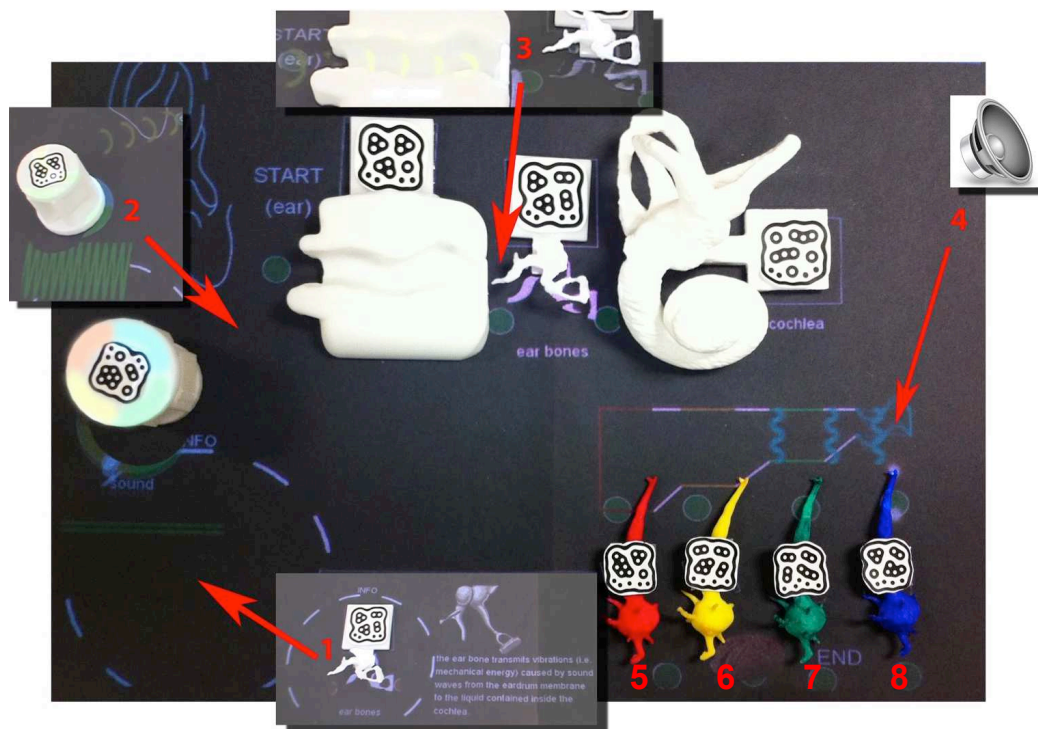

Figure 2. The EarExplorer Interface, after the users have connected all the tangibles in the correct sequence. They use the infobox (1) to learn about the different organs and connect them together; they then generate sounds at different frequencies with a speaker (2); sound waves travel from the emitter through the ear canal to the ear bones (3); finally, the sound reaches the basilar membrane inside the cochlea, activates a specific neuron and replays the sound if the configuration is correct (4).

4. The snail-shaped part of the **cochlea** contains the basilar membrane, which react to different sounds frequencies: the base is thicker and reacts to high-energy (high frequency) sounds; the apex (i.e. tail) is thinner and react to low-energy (low frequency) sounds. When students connect the cochlea to the ear bones, they see the basilar membrane being unrolled bellow the tangible. To stress this transition, a short video pops up in which a teacher reiterates that the membrane is unrolled to facilitate their task.

5-8. In this step, **four neurons** need to be correctly sequenced bellow the cochlea to rebuild the basilar membrane. Each neuron is associated with a particular thickness of the membrane, and a particular sound frequency. Each neuron is color-coded according to the coding scheme displayed on top of the speaker (from low to high frequencies: blue, green, yellow, red). We simplified the behavior of the system to provide an intuitive feedback when a sound wave reaches the basilar membrane: if the order is correct, users will see the part of the membrane associated with this neuron vibrate, followed by electrical potentials travelling through the neuron (Fig.2, bottom right corner, blue neuron), and the audio sound being replayed. If the order is incorrect, the membrane does not vibrate, the electrical potential does not reach the brain and no sound is played.

Method

Participants

38 college-level students took part in this study (average age 22.5, SD = 6.2; 26 females, 12 males). Participants completed the experiment as a requirement of a psychology class. The pre-requisite for registering was to not have any prior knowledge of the human hearing system. This population of students hence was very likely to be novice learners when it comes to the human hearing system.

Materials

The first activity involved rebuilding the human hearing system using EarExplorer. Students had 7 objects that they needed to connect between the outer ear and the brain: an ear canal, several ear bones, the cochlea and 4 neurons, as outlined previously. In the "listen" condition, students followed a step-by-step recorded guidance of a professional instructional designer. The instructional designer was not aware of our research hypotheses and was asked to make the learning material as engaging as possible. In a second activity, participants were asked to read a two-page summary describing the human hearing system. We retrieved the text from an educational website, whose goal is to simplify complex concepts to make them more accessible to a wider audience. The original text was four pages long; we removed paragraphs where the level of details was beyond the learning goal of this activity.

Finally, the learning test asked students to: 1) label the organs of the earing system; 2) describe various sound waves and asked which parts of the basilar membrane would vibrate at those frequencies; 3) compare the effect of various kinds of lesion (e.g. do broken ossicles have the same effect as piercing the eardrum?); 4) describe which part of the basilar membrane should be numbed to lose sensitivity to certain frequencies; 5) map the frequency range of various animals (bats, dogs, mice) inside their cochlea; 6) describe how sound is propagated from one organ to the other. Each learning test (pre, mid, post) had small variations in the questions.

Design

We used a between-subject experimental design (Fig. 3): in the control group, students followed the instructions of a teacher demonstrating how to build the human hearing system on a video ("listen"). In the treatment group, students built the hearing system without guidance ("discover"). The teacher used EarExplorer in the video, and described each piece of the TUI as well as each of the steps necessary to complete the task.
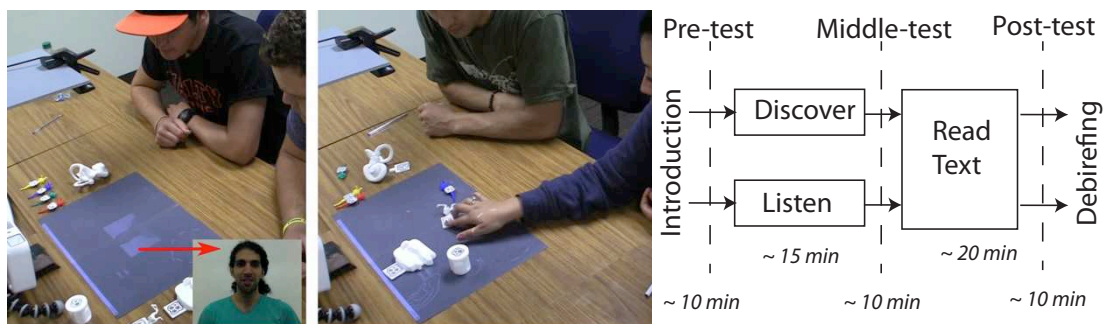

Figure 3. The two experimental conditions of our experiment (left: "listen", with the video of a teacher guiding the students through the activity; middle: "discover", where students rebuild the earing system by trial and errors. Right side: the experimental design of the activity.

Procedure

We ran the study in 4 consecutive days, over ~20 hours with 38 participants, doing the study in pairs. Each pair was formed randomly. Each pair had an hour to complete the study. Upon students' arrival, an experimenter explained that they would be working on a collaborative task and described the structure of the study (i.e. pre-test, hands-on activity, middle-test, second activity, post-test). Students then took the pre-test, which all participants finished in less than 15 minutes. Participants then completed the first activity. In the "listen" condition, they were asked to rebuild the human hearing system by following the instructions of a presenter. Participants in the "discover" condition were asked to build the human hearing system by free exploration and by using the information box. Both conditions watched the same two-minute video describing the problem and the system: "John is deaf because his entire auditory system is missing. As you can see, there is nothing between his ear and his brain. Your goal is to help John hear again by rebuilding his auditory system! [...] At the bottom left corner of the table, there is an information box. By putting objects in this circle, you will be given more information about each piece of the auditory system". Students had 15 minutes to complete this task. They then took the mid-test for the next 10-15 minutes. During the second activity, students read a text describing the human hearing system and completed an activity where they analyzed different shapes of the basilar membrane and predicted the effect on the auditory range of the subject. They then recreated the shape with EarExplorer and compared their prediction with the output of the system. Finally, students were asked to take the post-test and were debriefed; we also informally asked them their opinion on the educational value of our system.

Coding

The learning test was coded in a binary fashion (correct / incorrect). Since the last question was open-ended, students received 1 point for a correct answer, 0.5 point for a partially correct answer, and zero points for a wrong answer. Log files were collected during the two activities involving EarExplorer. We logged information when a fiducial was added and removed from the table, when a new connection was created, when sound waves were generated, and how many times the info-box was accessed. Additionally, we categorized each participant in a binary manner as being either the "leader" or the "follower" in the activity. This distinction is motivated by the work of Shaer, et al. (2011), who noticed that pairs of participants tended to assign "roles" to their members; for instance, in collaborative tasks there tends to be a "driver", who is physically active and controls the interface, and a "passenger", who is physically inactive and merely proposes verbal suggestions. Those profiles of collaboration allowed us to further analyze the collaborative dynamics of a group.

Results

The results supported the hypothesis that subjects in the "discover" condition learned more than subjects in the "listen" condition (Fig. 4). We subtracted the pre-test from the middle and post-test to compute learning gains, since students in both groups scored very low on the pre-tests and avoided a ceiling effect. A multivariate ANOVA showed that participants in the "discover" learnt significantly more after the first activity: $F(1,35) = 22.11$, $p < 0.001$ and after the second activity: ($F(1,35) = 16.15$, $p < 0.001$. There was no significant difference on the pre-test: $F(1,35) < 1$.
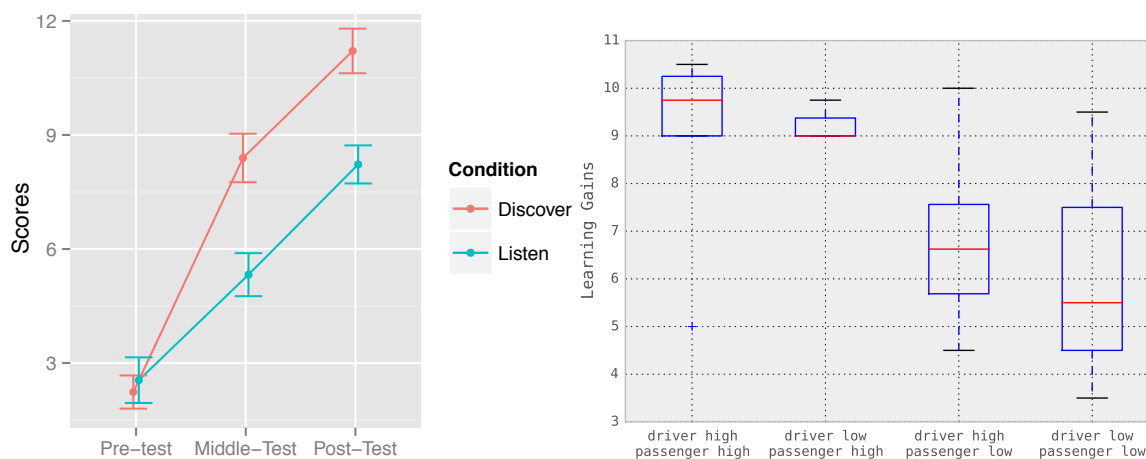

Figure 4. Left side: results on the learning tests with regard to the two experimental conditions. Right side: learning gains by types of group (e.g., "driver high, passenger high" means that both the leader and follower in the group were above the median split computed on the students' GPA).

We analyzed the log files at the dyad level, since the system cannot differentiate between users. As such, we only have 20 data points and thus we will also report results where the p-value is below 0.1. A multivariate ANOVA revealed that participants in the "discover" condition did more manipulation with the tangibles during the two learning activities with EarExplorer: $F(1,14) = 4.03$, $p = 0.064$ (number of actions for the "discover" condition, mean=162.56, SD=52.53; for the "listen" condition, mean=132.89, SD=25.55). They also consulted the info-box more often: $F(1,14) = 3.40$, $p = 0.087$ (for the "discover" condition, mean=14.22, SD=16.71; for the "listen" condition, mean=3.33, SD=1.22). Interestingly, the number of times that participants accessed the "infobox" was positively correlated with higher learning gains on the middle-test: $r(18) = .55$, $p = 0.018$. This suggests that that part of the learning, as measured with the middle-test, happened in the interaction with the information box, and that students in the "discover" condition were more likely to consult it.

Effect on students' school proficiency (GPA)

As a post-hoc analysis, we wanted to see if the effect would hold for students of different abilities. To this end, we categorized participants as being below or above a median split computed on their GPA. While there was no significant difference between groups in terms of students' GPA across the experimental groups, there were differences between pairs when classifying each student as being the "driver" or the "passenger" of the interaction (Shaer & al., 2011). The driver is the student who decides what the group does next, manages turn-taking and tends to be more physically active. The "passenger" takes less important decisions, tends to be more

passive and often merely proposes suggestions that need to be approved by others. There was not difference between drivers and passengers in terms of their learning gains. However, when this factor was crossed with a binary variable representing students' GPA (0 = below the median, 1 = above the median split) we found the following effect (Fig. 4, right side): As expected, groups with two proficient (i.e. both have a GPA above the median) students (first boxplot) had the highest learning gains and groups with two less proficient (i.e. both have a GPA below the median) students (fourth boxplot) had the lowest learning gains. What is interesting, though, is that being in a group with a low-GPA driver will make students more likely to learn: $F(1,37) = 5.26$, $p < 0.05$ compared to groups with a low-GPA passenger. Descriptive statistics suggest that this is more likely to be the case in the "listen" condition (mean = 9.00 for low GPA passengers versus 5.50 for high GPA passengers) compared to the "discover" condition (mean = 9.04 versus 8.83 for high / low GPA passengers). We did not test for significance for those results due to the low sample size of each group.

Users' comments on EarExplorer

Students' response was overwhelmingly positive. One participant said that she "would love to use a system like that in the classroom". Another mentioned, "It was nice to be able to build your own thing". The novelty of the interface sometimes had a negative effect on some students: some students stopped working on the task to understand where the projection was coming from and how the system could locate the tangibles. One even said "at the beginning I was more interested in understanding how the system worked than working on the task".

Discussion

In this paper we described the design of an educational TUI that supports students' discovery of the human hearing system. Our design was strongly influenced by interviews with students, as well as brainstorming sessions with experts in neuroscience. Even if our first prototype is in the early stage of its development, users responded positively to its design.

Our main contribution is an empirical study extending previous results found in our lab that that an exploration task on a TUI prior to reading a text instruction leads to higher learning gains than the other way around. The current study manipulated the level of guidance (close guidance vs self-driven discovery): we found that students who built the human hearing system with EarExplorer without guidance improved their learning gain from pre to post test by ~25% compared to students who followed the step-by-step instructions given by a teacher. Additionally, we found that students in this condition were more likely to take advantage of additional resources that provide relevant information to the task. We also qualitatively observed that minimally guided instruction facilitated students' exploration by having them produce incorrect systems, while students who followed the instruction of a teacher always immediately produced a perfect solution. This tendency to explore the problem space is supported by research showing that students *need* to make mistakes when learning about new concepts (Kapur, 2008). Thus, our findings suggest that a well-designed TUI activity for self-driven discovery might prepare them to better learn from a text-based instruction compared to students following step-by-step instructions. In order for such a TUI to be considered well-designed, the system does not only have to allow students to make mistakes, which could be achieved simply by increasing the complexity of the activity. Importantly, the system has to enable students to act on these mistakes such that the action advances their understanding of the phenomenon under investigation. This can be achieved by designing implicit scaffolds into the TUI. In EarExplorer, the scaffolds consist of the restricted number of tangibles, their shapes, and the animation upon correct connections. Without these implicit scaffolds, we believe that the self-driven discovery activity would be too unstructured for the students to learn from their actions and mistakes.

Finally, we found an interesting interaction effect between students' school proficiency (as measured by their GPA) and the group dynamics (i.e., who is driving the interaction): Groups with a low-GPA driver and high-GPA passenger scored higher on the test compared to groups with a high-GPA driver and a less proficient follower. Followers who are less competent than their peers were less likely to involve themselves in the activity, because it might seem that they did not believe that they could make a significant contribution, or because they were put in a clearly passive observer role. When they took more responsibility (i.e. by being a driver), in combination with a proficient peer engaging in the activity with them, we saw those students perform as well as high-GPA participants. It is important to point out that the students did not know anything about each others' GPA scores. Hence, this result suggests that group activities are more beneficial for dyads when the less proficient (in terms of GPA) student is in control of the TUI. Being put into the passive observer role, the less proficient students were least likely to gain anything from the task. As such, this provides some insights on how to socially engineer group activities, as we believe that mixed-proficiency groups have advantages that both benefit the less proficient and the more proficient students.

Conclusion

TUIs possess an untapped potential for introducing students to new concepts. Previous research on interactive tabletops mostly focused on tangibles as interaction devices (e.g., Shaer & al., 2011). Few researchers have tried to fully exploit the representational effect TUIs for discovery-based learning. Our contribution is to provide preliminary design principles and empirical results to this new domain.

Taken together, our results suggest that educational TUIs better support learning when novice students have the possibility to explore the activity without explicit guidance compared to following step-by-step instructions. In order to build their intuition, students need the freedom of trying things, making mistakes and revising initial ideas to build their own micro-theories of a phenomenon. Just physically going through each step of the activity was not enough to build that prior intuition. An important feature of TUIs designed for discovery learning activities is that they allow designers to construct a rich space that enables a big variation of interactions, and keeps the activity complex and realistic, while at the same time cutting out unnecessary noise, and restricting the space of possibilities to prevent students from getting overwhelmed. By offloading explicit guidance to implicit design features, TUIs seem to be well-suited for novice students engaged in discovery-based activities. As such, TUIs have the potential to open the door for authentic learning activities into the classrooms in an effective way. If we find out more about how to use TUIs for this goal, we might concretely contribute to enriching students' experiences in schools in a sustainable way.

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