Tabletop Displays for Small Group Study: Affordances of Paper and Digital Materials

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ABSTRACT

In this paper we compare the affordances of presenting educational material on a tabletop display with presenting the same material using traditional paper handouts. Ten pairs of undergraduate students used digital or paper materials to prepare for exams during four one-hour study sessions over the course of a term. Students studying with the tabletop display solved problems on their own before resorting to answer keys and repeated activities more often than students studying with paper documents. We summarize study activities and discuss the benefits and drawbacks of each medium.

Author Keywords

Tabletop, paper, education, affordance, collaboration, study

ACM Classification Keywords

H5.2. User Interfaces, H.5.3. Collaborative Computing

INTRODUCTION

There is growing interest in exploring multiuser multitouch tabletop displays. This is driven by the decreasing cost of projection technology, increasing availability of multitouch facilities, and the resulting potential to support natural simultaneous interaction of multiple individuals with digital materials. Research has demonstrated that tabletop displays are useful for gaming and entertainment [35], manipulating photos [2], communication [20], and education [10, 21, 28]. Educational applications are especially promising because of the potential benefits of shared equable interaction. Although multiuser tabletop display systems are a common component of visions [4, 16, 17] for the "classroom of the future," their pedagogical benefits remain unclear. Relatively few studies have addressed the tradeoffs between paper and digital materials on tabletops (see [32]), but none have addressed these tradeoffs in the context of collaborative learning. This paper presents a research study

that compares how pairs of students interact with digital and paper materials on a tabletop display. Specifically, we examine interactions of students studying neuroscience diagrams in preparation for exams to address the following questions:

- How do large, horizontal, multiuser displays affect cognitive and social activities in a shared study environment?

- What pedagogical benefits do tabletop displays provide beyond a motivating context for activity?

We conducted a comparative study with ten pairs of undergraduate students from an introductory cognitive science course at our university. We collected over 40 hours of observations as these students discussed, annotated, and studied using digital and paper diagrams. Our research team worked closely with the course professor in preparation of materials and to ensure an authentic context for evaluation of how tabletop displays affect group study in an on-going class. We implemented a simplified tabletop application with limited features as a way to collect initial data on which features might be useful for future educational tabletop applications. Findings address issues of task participation, engagement with study material, and general group work dynamics.

BACKGROUND

While the focus of this study is the affordances of paper and digital study materials in one specific situation, the long term goal of our work is to understand the cognitive ecology of physical and digital media. Here we briefly review tabletop applications for education and single display groupware, as well as our motivation for selecting pair study groups and issues associated with learning with digital and physical materials.

Tabletop Applications for Education

The benefits of presenting educational content on a tabletop display are currently unclear. Within the domain of tabletop research, few applications are designed with explicit educational goals or evaluated for educational outcomes. The educational applications that have been created focus almost exclusively on younger populations, mainly children from age 4 to 13, and are primarily exploratory in nature.

For example, research has examined how tabletop displays facilitate learning numbers, sorting, and patterns [10], learning to read [28], and social skill development [21]. Findings from these studies emphasize the motivating nature of tabletop displays and report higher task engagement compared to other mediums. While these findings are valuable and suggestive, the pedagogical benefits of cooperative tabletop activities need further exploration.

The main body of research on tabletop displays examines interaction techniques (e.g., [19,39]), with some investigation of issues of territoriality [25] and social protocols [15] around tabletops. While undergraduate students are a common choice for participants in tabletop research studies, there is little research that addresses the educational implications of tabletop displays for this user population. In addition to wanting to better understand the pedagogical benefits of tabletop displays for undergraduate education, we decided to focus on pair study groups of college students for several reasons.

First, collaborative learning is strongly encouraged by most universities, and this study practice differs from what many students experienced in high school. While college students typically need to turn in individual assignments, many professors encourage students to form study groups, seek help from teaching assistants, and work with more advanced students to learn course material. The collaborative nature of tabletop technology has potential to naturally support this form of small group study.

Second, implementing tabletop educational activities within a university setting is logistically easier and more feasible than other educational settings. Most college courses have teaching assistants who can help with activity design and setup. College students can be expected to complete tabletop activities independently with minimal supervision.

Finally, tabletop systems are able to record how students interact with projected materials during joint study sessions. This provides the course instructor with data about the process of engaging with course material in a social study setting outside the classroom, a new and potentially valuable source of data about mastery.

Single Display Groupware
Unlike traditional computer workstations with a single keyboard and mouse, tabletop displays allow multiple learners to have equal access and shared ownership over the activity. The broader category of display technology that accommodates multiple users is called single display groupware (SDG) [30]. SDG has been shown to lead to greater task engagement and activity participation [31] (also see [34] for an interesting SDG toolkit). Active engagement and equitable participation in a task are necessary aspects of collaborative learning. Multiuser multitouch tabletop displays seem inherently well-suited for facilitating this type of behavior. Compared to vertical displays their

horizontal form factor provides a more neutral and equitable surface for collaboration [24]. The physical size of the tabletop provides ample area for multiple people to interact with content. Finally, multitouch capabilities allow multiple people to simultaneously discuss, annotate, and manipulate digital artifacts.

Digital and Paper Media
Sellen and Harper, in their seminal work on the myth of the paperless office [26], document key affordances of paper. They note that a simple dichotomy of paper versus digital is insufficient as a framework for understanding the cognitive ecology of real-world activity with paper and digital artifacts. While ultimately we need to understand this complex tradeoff space, it is still vitally important to delineate specific advantages, disadvantages, and differences between media. Terrenghi et al. conducted an exploratory study that examined the affordances of interacting with physical and digital media on tabletops [32]. Their observations provide insights for designers interested in creating digital interactions that mirror interaction with real-world objects. Previous research has also demonstrated that social protocols typically employed around traditional tables with paper materials are insufficient for group work around shared digital documents. Collaboration with digital documents requires coordination policies at the software-level [7, 15, 29].

Within educational research, substantial attention is given to the difference between learning with virtual versus physical materials, e.g., [5, 12, 33]. This research focuses on the pedagogical benefits of manipulating physical objects instead of two-dimensional virtual objects on a computer screen. While this body of work is relevant, our primary focus concerns the affordances of paper and digital materials presented on tabletops.

Differences in Approach
Our evaluation builds on earlier work but is different in several respects. We examine how digital and paper materials affect study practices including student participation and cooperation. Our tabletop application (described in detail below) is not the focus of this research. It is purposely minimalistic. We created a basic application that would be quick to learn and simple to use. While we have plans to explore a variety of facilities, we wanted to first look at how using a basic application compared with using paper materials. Another difference from earlier tabletop research studies is that we study interactions over multiple sessions to ensure that observed behaviors are not an artifact of first-time use.

CONTEXT OF STUDY
We examine how pairs of undergraduate students work together to discuss and interact with diagrams provided in a neuroscience class at our university. This course was of particular interest because of the professor's instructional techniques and classroom practices. The professor has

taught this class in the same format for seven years. To explain course concepts she uses a combination of hand-drawn and computer-generated diagrams on overhead transparencies. During lecture, the professor begins explaining a topic by placing a single transparency on the overhead. Throughout her explanation she adds layers of complexity with additional overheads and moveable cutout parts.

We selected this course as a focus for understanding cooperative group study with tabletop displays for several reasons. First, diagrams and visuals are pervasive throughout all course lectures, handouts, and textbooks. Digital tables are well suited for displaying this type of highly visual information. Second, the tabletop display can be used as a digital analog to the professor's overhead projector and transparencies, allowing students to manipulate multiple layers of information just as the professor does in class. Third, there is a low cost to transfer instructional materials (i.e., diagrams for labeling, graphs to draw) to a digital format for the tabletop display. This was done in a few hours by one researcher, but an instructor could easily adapt future overhead transparencies or PowerPoint slides to tabletop activities. Fourth, this course requires substantial out-of-class study time. Students in the class were motivated to participate in our study because it provided them with course materials and cooperative study time.

TABLETOP TECHNOLOGY
We implemented a basic tabletop application using a MERL DiamondTouch table [4] and the DiamondSpin toolkit [27]. The tabletop application was designed so that the students' experience would mirror interaction with paper materials as well as the professor's practices with materials in class. Prior to each study session, a set of activities was preloaded into the tabletop system. The interface allows students to view one activity at a time, much like the professor does with an overhead projector and diagrams in class. Also similar to the professor's techniques, our tabletop application lets students add additional layers of information by stepping through phases of a process or turning on an answer layer to check their work. The activity content is a static diagram; that is, students are unable to rotate, resize, or move images. Chairs next to the tabletop and interface controls are positioned so that students would sit side-by-side instead of across from each other. This allows for ease of sharing text-based material. Each student has their own "draw" and "erase" buttons that allow them to mark on the diagrams with their finger (see Figure 1). They can also erase each other's annotations. This mirrors paper interactions where students can erase each other's drawings with a pencil eraser. Students have access to a shared menu that allows them to navigate between activities (including previous weeks' activities), view activity answers, and clear all annotations on the current document. When students display the answer layer, the answers appear in green on top of their
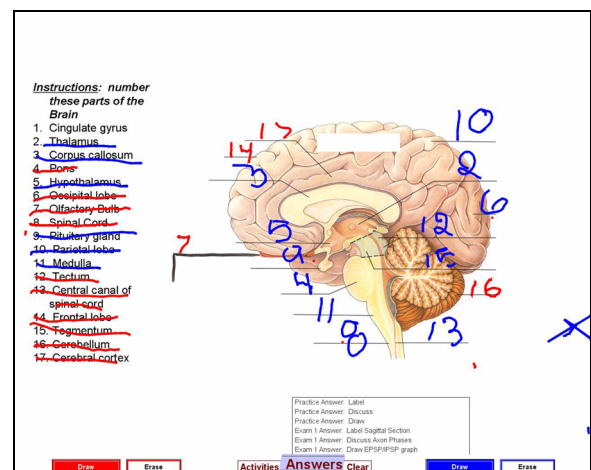

Figure 1: Screenshot of tabletop application with labeling activity; users have individual draw and erase controls and a centralized menu; currently in view answer mode.

annotations so they can check their work. We designed the tabletop application so that annotations and notes would persist over multiple sessions in a way similar to how pencil markings persist on paper. Our system exports each group's annotations and reloads them when the pair returns for a subsequent session.

METHOD
To assess the tradeoffs of supporting group study with a digital table, we conducted an evaluation with 20 undergraduate students from an introductory neuroscience course. Successful students in this course need to memorize brain anatomy, understand and describe complex systems (e.g., firing of a neuron), and be able to generate graph and circuit drawings of various brain activity.

Participants and Procedure
Ten pairs of undergraduate students (n=20, mean age=20.15, 15 females) participated in the five week study. All students were enrolled in the same undergraduate course on neuroscience at our university. Each student picked a partner at the beginning of the quarter and worked with this person throughout the study. None of the participants had worked with their partner nor used tabletop technology prior to the study. All pairs of students attended four one-hour "study sessions" over the five-week condensed summer term. We observed over 40 hours of study time with this group of students. Experiments involving tabletop displays rarely examine repeated use by the same participant group. We chose to conduct multiple trials with the same students to observe behavioral patterns over time. Students in this class were highly motivated to participate, and we had a remarkable attendance rate—all 20 students attended all four sessions. For participating, they received either extra credit or a cash incentive of $50.

Each study session was comprised of the three activities that had been selected by the course professor: (1) an anatomical labeling activity, (2) discussion of a dynamic

system, and (3) a drawing activity involving a graph or circuit. The goal of each study session was to prepare students for an upcoming exam by reviewing relevant diagrams. Study sessions were held the two days prior to each exam. At the beginning of Study Session 1, all students were given three practice exercises (one for each activity type listed above) so they could become familiar with the activities they would see and the way in which they would be presented.

Our goal was to keep the students' experience as authentic and relevant to the course as possible. Students were informed that their professor selected all study activities specifically to prepare them for the upcoming exam. Before Study Session 1, students were told that they could use this time however they choose and could use personal notes or books. If requested, we provided color copies of diagrams for students to take home. All study sessions were conducted in our laboratory around a DiamondTouch table to keep the environment and workspace consistent across conditions.

Conditions
Pairs of students were randomly assigned to the paper or digital condition. In the paper condition, students received one set of paper diagrams to share and erasable colored pencils. Students in the digital condition worked with digital images on a DiamondTouch table (79cm diagonal, 4:3 aspect ratio) where they annotated images by touching with their finger. In both conditions students had access to their materials from previous study sessions as well as their personal notes and textbooks. To distinguish the notes and annotations each participant made on the diagrams, one student in each pair was the "red user" and the other was the "blue user" for the entire study. The activity content was identical in both paper and digital conditions; however, the size of diagrams varied. In the paper condition, diagrams were printed in color on an 8 ½" x 11" sheet of paper. Diagrams in the digital condition were approximately twice that size and unlike the paper version are not rotatable or resizable. We considered giving students in the paper condition diagrams equal in size to the digital diagrams but chose to provide handouts of standard size to reflect classroom practices. Variations in diagram size and rotatability between the two conditions provided interesting results that are discussed below. Students in the paper condition received folders with activities and answers while students in the digital condition had access to a menu on the interface that opens activities and answers.

RESULTS
The following results are based on observations of 40 testing sessions observed live and reviewed on video. We used two-sample multivariate t-tests for planned statistical comparisons with α=0.05. Error bars on graphs represent standard error. Most coding was straight forward (e.g., students either repeated an activity or they did not) and

performed by one researcher. Coding methods and scores were cross-checked by a second researcher.

Integration with Current Study Practices
One open question concerning digital study materials is how students learn to use the tabletop application and integrate it into their current study practices.

Learning to Use the Tabletop Application
Students in the digital condition did not have problems learning to use the tabletop application. All students received five minutes of training before starting the three class-related activities. During the training period, students quickly learned how to turn on and off drawing and erasing, navigate between different activities, view answers, and clear annotations. We conducted a brief survey with participants in the digital condition just before Session 2. Eight of ten students said learning to use the table was "easy" and two others said it was "very easy" (five-point Likert scale; zero neutral with "very hard" and "very easy" as endpoints). Similarly, eight of ten students reported that it took them less than five minutes to learn to use the system. The other two students said it took 5-10 minutes to learn to use the system.

Novelty Effects
One aspect of tabletop displays is the novelty of the device. We anticipated that the newness of the technology would distract participants from the task, resulting in some off-task behavior, but there was actually limited off-task behavior during the study session. Most off-task behavior occurred at the end of a session after students completed all study activities. Overall, the novelty of the device did not appear to interfere with the task.

Incorporating Existing Paper Materials
Students in both conditions were told that they could use their own materials during the study session. We expected students in the digital condition to be less likely to incorporate paper notes, notebooks, and textbooks because the materials might obscure the tabletop display space. Our observations indicate exactly the opposite; just as many students in the digital condition used personal study materials (2 pairs during week 1, 4 pairs week 2, 2 pairs week 3, 0 pairs week 4) as those in the paper condition (2 pairs week 1, 2 pairs week 2, 1 pair week 3, 1 pair week 4). Students in the digital condition did face problems negotiating tabletop space and organizing their materials on the top-projected display surface. Students fumbled with materials, often setting them on their lap or on a nearby stool. Several students placed notebooks and loose sheets of paper on the tabletop surface, even though the overhead projector projected onto these materials.

Activity Participation and Work Flow
We requested that students stay at least 15 minutes for each study session, but they could leave anytime thereafter. Figure 2 indicates the average time students stayed and

provides a breakdown of average time spent on each activity type. Time-on-task data were collected based on video timestamps according to when students started and stopped each activity. We did not include time spent in off-task behavior (e.g., student breaks from activity to answer a cell phone). Average weekly study time was approximately equal for both mediums (paper overall mean=24.8, stdev=9.4; digital overall mean=24.5, stdev=8.8), but there were differences in how long students worked on each activity depending on condition. The average time spent on the discussion activity was greater in the paper condition. We observed two contributing factors to this difference. First, the tabletop display was more efficient for managing materials, and students with paper documents had to flip through and sort discussion slides by hand. Second, students using paper documents made more detailed notes on the discussion diagrams (we address this in the discussion activity section below).

Repeating Activities
Interestingly, students with digital diagrams went back and repeated activities more often than students with paper diagrams. All pairs in the study completed each activity at least once, but some pairs went back to an activity, erased their answers, and tried it again. Figure 3 illustrates how many pairs in each condition performed an activity more than once. On average students in the digital condition repeated an activity twice as often as students in the paper condition (paper overall mean=1.3, stdev=0.96; digital overall mean=3.0, stdev=2.0).

Repeating an activity often required students to erase previous answers, and this was more easily done in the digital condition. One student working with digital documents said, "Want to try to redraw it?" Their partner responded, "I mean, we could just for memorizing it." The pair quickly cleared the annotations and began drawing again. Most students working with paper documents who wanted to repeat an activity spent time erasing previous annotations. On several occasions it took one full minute to erase annotations on a single diagram. Other groups flipped the paper document over and redrew the diagram on the back of the paper instead of erasing.

Labeling Activity
Being able to label items on a diagram is an important course objective. We anticipated that students working with digital documents would more equally share the labeling task. Equal participation means that on average students would each contribute 50% of the answers. We found that on average a student in the paper condition contributed 76% while their partner contributed 24% (stdev=18). Among students working with digital documents, one partner on average contributed 63% while the other contributed 37% (stdev=7.9). This is not a statistically significant difference, but it has implications for how students organize themselves to complete this shared activity.
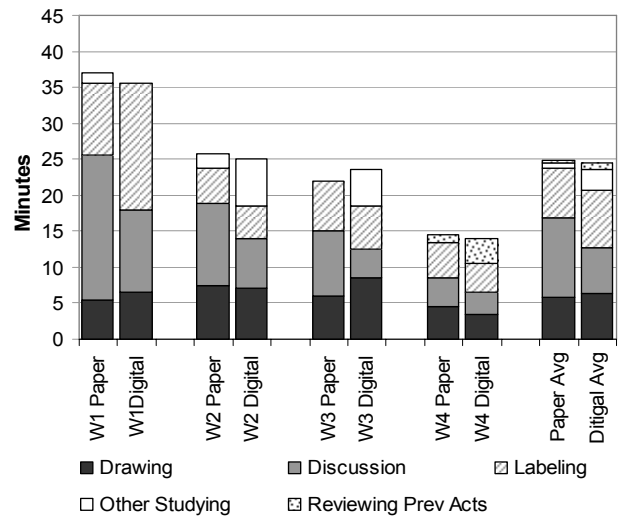

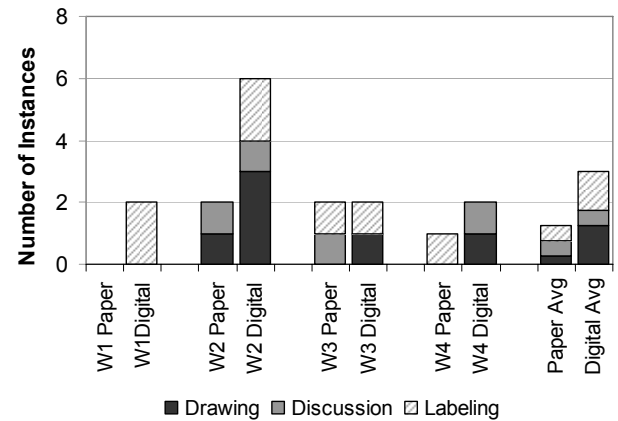**Figure 2: Average time students attended each study session with breakdown for each activity.**

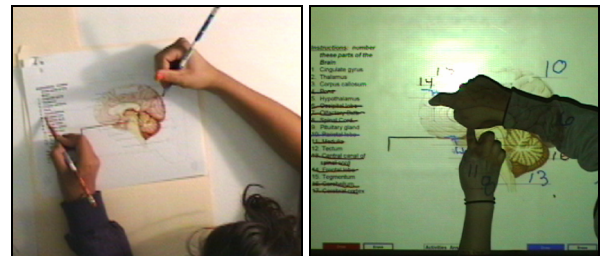**Figure 3: Number of instances an activity was repeated.**

Figure 4: (left) student labels items on the paper diagram while partner crosses off items; (right) both students label digital diagram at the same time.

The two mediums provide contrasting use cases (see Figure 4). First, students working with paper documents most often followed a serial strategy when labeling the diagram. These students tended to divide up the task labor; one student wrote down answers while the other student crossed off items from the numbered list of parts to label. While adopting this work pattern means that one student does the

majority of the labeling, it allows students to jointly focus on all of the aspects of the diagram. An alternate pattern of work was observed with digital diagrams. Here, both students performed labeling and crossing off tasks, often reaching across the surface to interact at the same time. This approach allows both students to engage with the study material and practice labeling the diagram, but students may miss part of the activity if they do not carefully attend to their partner's actions.

Discussion Activity

A central question is how the mediums support and constrain discussion between students. In both conditions, the typical flow of work during the discussion activity involved one student explaining the concept to their partner. We categorized the way in which students used the paper and digital mediums during discussion: all verbal (no annotations made), sketching, written words, or both sketching and writing. As summarized in Figure 5, students in the digital condition used sketching most often (65% of the time) while students given paper handouts were more varied in the techniques used to support discussion.
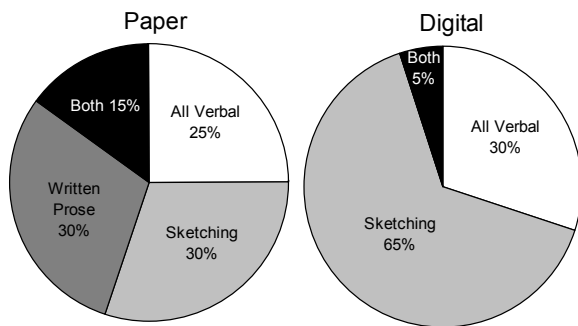

Figure 5: Techniques students used to augment discussion.

In the paper condition, students used pencils to make detailed notes on the diagrams, thus resulting in more time spent on this activity. When students sketched on paper, they did it lightly, perhaps so as not to leave a dark hard to erase mark on the paper. Notes and drawings in the paper condition appeared much more planned and structured. In contrast, students in the digital condition rarely wrote out full words or sentences during discussion. More often their answers were abbreviations, symbols, or numbers (see Figure 6, right). There was heavy use of sketching to
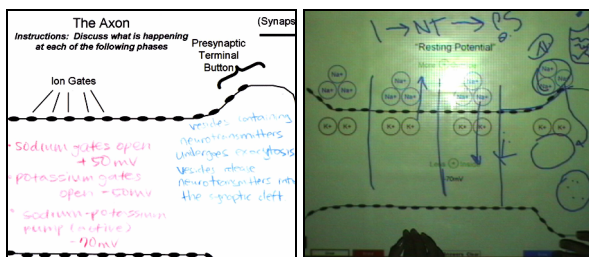

Figure 6: (left) written words in bullet points on a paper diagram; (right) rough sketches that accompany verbal explanation on digital diagram.

augment dialog. One issue is that current finger tracking capabilities and resolution of the tabletop display made writing legible sentences challenging (although there are interesting techniques [1] being explored to minimize this issue). Future evaluations should consider including stylus or pen based entry as well as handwriting recognition that transcribes notes into text.

Another key difference between the paper and digital discussion activities is the amount and frequency of erasing annotations. We observed students in the digital condition frequently erasing all of their annotations after explaining a concept to their partner. In contrast, and in agreement with [11], students in the paper condition crossed out annotations instead of completely erasing them, creating a rich history of learning. Instances of erasing in the paper condition occurred when students wanted to re-label a diagram or redraw a graph for extra practice, whereas erasing was the normal course of action after students in the digital condition finished an activity. An erase feature in digital media has both positive and negative consequences. We described these tradeoffs in the discussion section.

Drawing Activity

The main difference between conditions for the drawing activity involves single-user versus multi-user drawing. Remember that students in the paper condition were able to move and rotate study materials, while students in the digital condition did not have that option. As expected, students in the paper condition moved diagrams closer to themselves when annotating, especially during the drawing activity (Figure 7, left). Paper diagrams were rarely positioned in the middle of the table for both students to annotate. Again, we observed a serial work strategy around paper documents. In practice this means that one student drew on the paper diagram while the other student watched, thus taking on a more passive role in the activity. On occasions, however, students in the paper condition switched roles and passed the paper between them so each could draw.
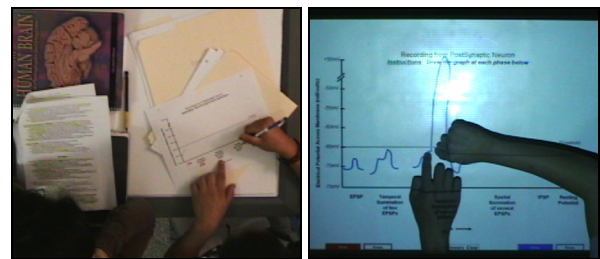

Figure 7: (left) student orients paper towards her when drawing; (right) one student draws the first three curves on the graph, then the partner reaches in to correct a mistake.

The digital medium affords multi-user drawing. Even if one student does most of the drawing, the digital table allows the partner to reach in and add to the solution. We observed at least one instance of this multi-user drawing behavior in each study session with digital documents (Figure 7 and 8,

right). The ability to draw in parallel on digital documents means that both learners have access to the materials at the same time; however, the students may focus on different parts of the task and not experience the entire problem solving process. Instances of simultaneous drawing (or drawing in parallel) were not observed with students in the paper condition.
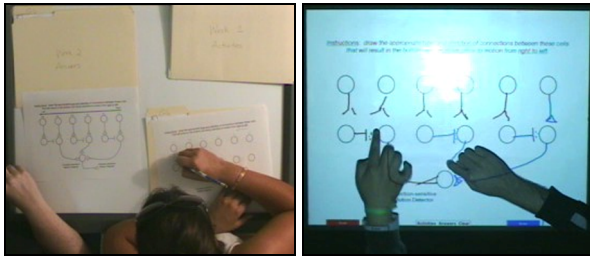

Figure 8: (left) student draws on paper document while partner watches; (right) students draw together.

Viewing Answers

We were surprised by a striking difference in how and when students in the two conditions viewed the answer key. Students in the paper condition more frequently looked at the answer key before attempting to complete the activity on their own. Figure 9 indicates the number of pairs who viewed an answer key before attempting the activity or guessing at the answers (paper overall mean=5.0, stdev=1.6; digital overall mean=0.3, stdev=0.5). The difference between paper and digital averages is significant (t(6)=5.56, p<0.0014).

Consider the following examples where two pairs of students solved a brain circuit drawing activity. A pair in the paper condition looked over the drawing activity quietly for about 30 seconds. Then the pair had the following conversation:

S1: "Ok, I don't know much about these cells. I'm not going to lie."
S2: "Did you want to guess?"
S1: "No, I have no idea. Seriously."
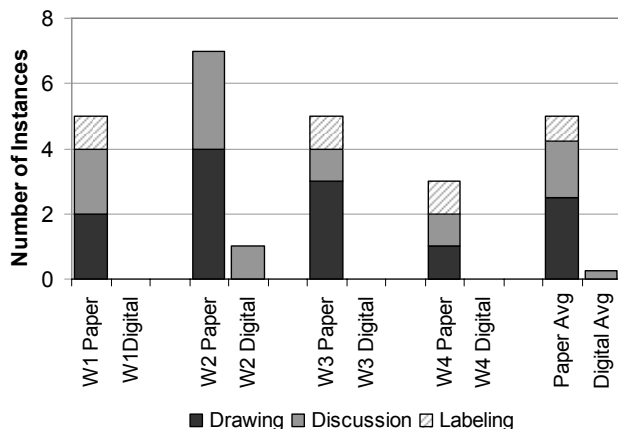S2: "I could guess, but then I'd like be teaching myself completely wrong."

In contrast, a pair of students working with digital documents faced a similar problem with the same drawing activity. This pair also looked at the diagram quietly for about 30 seconds, and then had the following conversation:

S1: "Do you have any idea?"
S2: "I'm still pulling it together."
S1: "Do you want to see the answer?"
S2: "No, let's take a guess." (*draws solution*) "I bet it's like that."
S1: (*opens answer key*)
S2: "Damn, I was close!"

We argue that the low cost and low risk of annotating on digital documents encourages students to guess and explore multiple solutions in a way that paper documents do not. In contrast, students in the paper condition used answer keys strategically as a way to study before attempting the activity. Writing the correct solution on paper seemed to be more important than guessing on their own first. Consider another pair of students using paper documents. This pair solved about half of a labeling activity. Then Student 1 asked her partner, "Do you want to look at the answers first and sort of study that before we do this [activity]." Her partner pulled out the answer sheet. The pair studied the answers for about two minutes and then returned to the partially completed activity. While a number of students in the paper condition used answer keys to study before completing the actual activity, some of these students verbalized negative associations with this course of action. For example, a student pair working with paper documents had trouble with an activity. One student laughed, pulled out the answer key, and said, "Let's just cheat and go straight to the answers." Interestingly, references to cheating, teaching oneself wrong, and using answers to study before attempting the problem were not observed in student interactions with digital documents.

Exam Scores

Finally, we provide data on student performance in the class depending on their treatment condition (see Figure 10). Twenty-nine students were enrolled in the neuroscience class, and 20 of these students participated in our study. The nine students who did not participate in our study were
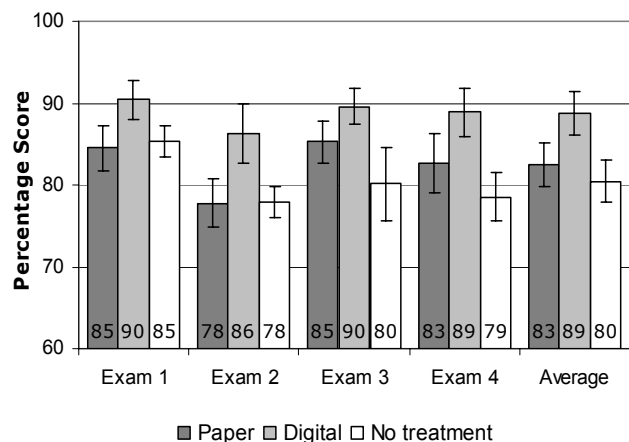

Figure 9: Number of instances an activity answer key was viewed before completing the activity.

Figure 10: Mean exam scores for students in course (N=29).

given access to the same study materials in paper form. Exam scores for students in the digital condition are significantly higher than students who received no treatment ($t(17)=2.26$, $p<0.04$), but students in the digital condition did not perform significantly better than students in the paper condition ($t(18)=1.67$, $p<0.12$). The difference between students who received paper materials during our study and students who did not participate in the study was also not significant ($t(17)=0.54$, $p<0.6$). While there is a trend in the data to suggest that students may perform better when given digital materials, other factors should also be considered. Students who decided to participate in the study may be those most motivated to perform well in the course. While we randomly assigned students to the two conditions, due to the small sample size other factors not controlled for such as GPA, year in school, and major may have differed between conditions. In our view, it is not the suggestive exam difference that is important but the clear differences in the affordances of paper and digital media.

DISCUSSION
Both the paper and digital mediums have unique and complementary affordances for small group study. Students working with paper materials made detailed notes and employed more serial work strategies. On the other hand, students in the tabletop display condition discussed ideas before resorting to answer keys, repeated activities, and performed better on exams. While a longer study with more students is necessary, we start to delineate the cognitive, social, and pedagogical affordances of paper and digital materials for small group study.

Cognitive Affordances
Paper is the normal media for most educational content. Students commonly interact with paper documents in group study situations. While participants in our study had no previous experience with collaborative tabletop learning environments, they certainly had little difficulty adapting to using the system we provided. In fact, the newness of the digital tabletop medium encouraged a certain freedom in their interaction. There was playfulness in how students annotated with digital ink that was not apparent with pencil and paper interactions. Similarly, the low cost and low risk of digital annotations encouraged students to spontaneously create drawings to support discussion. These impromptu sketches can support the learning process in cognitively important ways; the sketches provide an external representation of what students are discussing and may be important scaffolding for their developing understandings. Students working with paper documents were more likely to flip over the diagram and sketch on the back instead of drawing directly on the image. While the digital media encouraged sketching on the diagrams, it also encouraged erasing. In contrast, annotations on paper documents were less likely to be erased. Students with paper documents could go back and review their notes and drawings, whereas students with digital materials often did not have the earlier representations available for subsequent reflection. Of

course, this is not an either/or rigid condition. The plasticity of the digital media allows it to be treated as a dimension with numerous interesting way points between the two extremes. The cognitive implications of allowing erasing of digital annotations merits further exploration.

Digital tables can also enable more dynamic and immersive experiences than traditional paper handouts. This has both positive and negative consequences. Studies of how people learn with diagrams indicate that digitally animated diagrams require people to notice, accurately identify, and then process diagram changes, resulting in higher cognitive demands than static paper diagrams [22]. In contrast, the large touch screen and interactive facilities of tabletop displays enable forms of embodied interaction that are different from interaction with paper materials. Theories of embodied cognition and recent empirical investigations suggest that engaging our bodies can both help and constrain how we reason about abstract concepts [3, 9, 18, 37]. The act of drawing or even tracing the answer graph with a finger is an embodied cognitive process that may lead to a richer understanding and internalization of an abstract concept [6]. A student working with digital documents described this: "Want to redraw it together to help memorize it?" Another student in the digital condition asked their partner, "You want to try tracing it [the answer key]? It's good practice." We expect embodied cognition to play a central role in understanding the cognitive aspects of interacting with multitouch surfaces.

Social Affordances
The large, shared nature of the tabletop display allows students to have equal access to materials and engage in parallel activity, but is this work flow best for learning? There are interesting differences between the observed parallel work patterns with digital documents and serial patterns with paper documents. On one hand, working in parallel means that both students have equal and direct access to materials, but this may cause one person to miss out on part of the activity or problem solving process. A serial work strategy also has positive and negative implications for learning. While both students jointly focus on the activity, one person is doing the majority of the work. The partner must play a more passive role.

Ideally the learning environment would encourage students to participate equally while maintaining joint focus on the task. Tabletop technology allows instructors to manipulate how educational materials are presented in ways that could reduce social barriers and engender equitable participation. Tabletop technology like the DiamondTouch allows instructors to encourage certain user actions. The DiamondTouch can sense each unique user and therefore restrict or allow certain interactions depending on who is doing them. The SIDES project examined the educational and social benefits of using this functionality to form group consensus and enforce turn-taking during game play [21]. More broadly, encouraging equitable participation through

cooperative gestures is a potentially valuable interaction technique for educational applications [14].

Pedagogical Affordances

The digital medium supports assignment repetition and self-testing in ways that paper medium does not. With the tabletop display, students can quickly erase previous answers and perform an activity again. Ease of erasing likely influenced why students in the digital condition performed activities more than once and were more likely to attempt a solution before looking at the answer key. Redoing an activity with a paper handout or erasing incorrect answers requires more time and effort. The forgiving nature of digital ink on the tabletop display allowed students to write down answers without being certain they were correct. Students in the paper condition were more careful about writing incorrect answers and were more likely to look at the answer key before attempting an exercise on their own. With both mediums, it is important to explore alternatives that allow students to save multiple copies of their work, allowing for easy assignment repetition without requiring time consuming erasing.

Tabletop displays are capable of providing instructors with valuable metrics regarding learning. The technology can log student interactions such as how much each student contributes to the activity, how many answers are correct, and when students look at the answer key. In our current work we are also exploring ways of augmenting study environments with multimodal tabletop displays. Specifically, we are exploring the capture of verbal dialogue while interacting with the table. This may provide useful feedback to the instructor as well as aid students in reflecting on previous work. Digital tables have the potential to dynamically scaffold learning in ways that static paper documents cannot. While the tabletop application in our study did not provide students with hints or scaffolding to help them with the activity, this is an area in which the digital medium might afford particular advantages.

One systemic issue with tabletop technology involves practicality and logistics of integrating the device into a real-world setting. Barriers for adoption of tabletop technology include its perceived educational benefit, initial cost, system upkeep, and content development. While paper materials are practical and obviously cheaper, given the evolution of toolkits [34] it is increasingly feasible for a professor or teaching assistant to implement tabletop activities for a class. It should be noted that our minimalistic tabletop application was created in several days, and content was created equally as quickly by a graduate student working in collaboration with the course professor. While our evaluation used a DiamondTouch table, other technology may fit better within existing classrooms. For example, rear-projected tabletop displays (e.g., FTIR systems [8]) can be built inexpensively in various sizes. Our laboratory is currently exploring portable FTIR tables that are easy to transport and setup. The area in and around the touch-sensitive interface is an additional design factor to consider. Tabletop displays with non-interactive outer edges would be useful for laying out paper materials. Finally, there is a large body of research examining the integration of paper materials onto the display surface [13, 23, 36, 38].

CONCLUSION

This paper presents findings from an evaluation that compares group study with digital materials on a tabletop display to traditional study with paper handouts. Results indicate that presenting materials on a tabletop display encourages students to attempt problems on their own before looking at answer keys and allows easy assignment repetition. While our results suggest that even a minimalistic tabletop application can benefit educational activities, subsequent studies with more students are necessary to fully understand this complex tradeoff space. In our view the goal is not to replace the medium of paper and pencil but to understand how tabletop displays and other digital technology can best fit with and augment existing educational ecologies.

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