Evaluating Augmented Idea Logs for Design Education

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ABSTRACT
Design students use a variety of physical and digital content in the course of their studies. Augmented paper interactions promise to address this tension, yet there have been few real-world evaluations of these systems. In this paper, we present results from the first longitudinal study of augmented paper interactions for student design teams. We describe our experiences with developing and deploying the iDeas learning ecology, a system that integrates digital pens and cameras into design practice. Across two quarter-long studies, fifty-eight design students used iDeas, authoring over 4,000 pages of content in the course of their classwork. We report on their design habits, the when, what and how of their notebook usage, and pinpoint further avenues of study, including device ensembles. Through observation and analysis, we discovered that integrated paper and digital interactions enable new practices, including the ability to instrument and study design activity itself. We then observe limitations of current form factor and maintenance that inhibit longitudinal use. We conclude by identifying guidelines for development and potential directions for future research into hybrid technology systems for creative work.

Categories and Subject Descriptors
H.5.3 [**Information Interfaces and Presentation**]: Group and Organization Interfaces — *computer-supported collaborative work*; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*input devices and strategies, interaction styles*; K.3.1 [**Computers and Education**]: Computer Uses in Education.

Keywords
Design education, Idea Log, collaboration technologies

1. INTRODUCTION
Design surrounds us through the objects we use at rest, at work, at play, to communicate, to plan, to achieve. Design students use a toolbelt of digital devices from desktop computers and laptops to mobile phones, digital cameras, and portable music players. Yet despite the ubiquity of these digital tools, many still depend primarily on paper for tasks both complex and mundane; in the so-called digital age, the use of paper is increasing [43]. Designers spread their work over both physical and digital artifacts, yet the two worlds live apart, and the common infrastructures for moving between them (scanning, printing) are heavyweight and cumbersome.

Previous work (*e.g.*, [8, 11, 16, 18, 19, 21, 29-32, 44]) has introduced augmented paper interfaces to address this tension between the physical and digital realms. Ethnographic work has shown the centrality of paper in work practices, especially for collaboration (*e.g.*, [17, 43]), and a few systems have used ethnographic work to inform system design [21, 30]. However, the number of field studies of augmented paper interfaces in daily work is small. Collaborage [29, 32] mentions a longitudinal deployment, but only anecdotally, and as part of a system study rather than a user study. Other research into augmented paper interfaces (*e.g.*, [19, 21, 31, 48]) has included short-term usability studies, but there have been no published reports on longitudinal deployments of these systems. From a methodological perspective, longitudinal use is the missing piece of the puzzle: *how does integrating physical and digital interactions actually change practice for users?*

Figure 1. Design teams in action. Students in the introductory HCI design class work with a variety of media during a group assignment. (Study 1)

We are interested in studying student design teams both to influence the development of physical and digital technology hybrids for education and as a way to inform interaction design for collaborative creative work in general. Design education, like other creative disciplines such as art and architecture, involves highly visual content (see *e.g.*, [25] for a description of "design thinking"). Two long-standing traditions in design education are the Idea Log [45], where students keep track of their design ideation and documentation; and the studio critique, where students display work-in-progress on the wall and present it to the class. More generally, project-based design courses feature interplay between times of individual ideation and reflection, and times of group presentation, discussion, and brainstorming—both in and out of the classroom.

As electronic media has emerged alongside physical media as a vital tool in education and design practice [22, 36], researchers have begun to examine the impact of new media in these domains. The CSCW literature has favored short-term collaborative

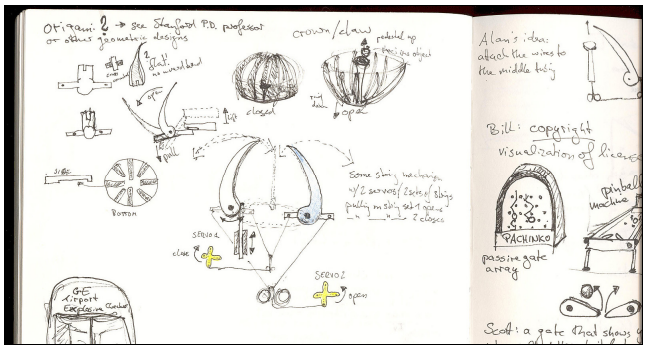

Figure 2. The Idea Log. A page of sketches from a student's design notebook.

episodes in studies [35], yet it is often hard to justify them as proxies for evaluating the ongoing relationships and long-term effects of collaborative technologies. The authenticity, wealth, and richness of data that longitudinal studies provide are hard to substitute, and recent research (*e.g.*, [5, 35]) attempts to both design and evaluate technology in longitudinal contexts.

1.1 Artifacts for Design Thinking

The *Idea Log*, also known as a design notebook or research notebook, provides a space for individual ideation and documentation (see Figure 2): students take class notes, record team meetings, and sketch, write down, and paste-in design observations, ideas, and inspiration. The studio critique provides a form of peer learning that is unique to the art and design disciplines. It is a forum for students to share work with classmates and for that work to be acknowledged. It offers an opportunity for students to comment on each others' work, to see common strands, and to offer suggestions and critique. Discussion with peers and instructors renders visible their diverse perspectives on the design problem and the multiple paths to its solution.

Currently, design students and practitioners use physical notebooks and walls for their expressive power, sketch-based interaction, and familiarity. The paper notebook remains the repository for ideas: it is an excellent medium for sketching, it is portable across varied contexts and scenarios, lightweight, and its "display" has infinite battery life. As Gershenfeld writes, "If the book had been invented after the laptop it would be hailed as a great breakthrough. It's not technophobic to prefer to read a book; it's entirely sensible. The future of computing is back in a book" [13]. Paper notebooks are reliable, robust, and easy to browse. However, search and reorganization of content in a paper notebook is challenging at best. Sharing design content is also difficult, which is problematic, considering that distributed teamwork constitutes the core of design practice.

Electronic media have begun to exist alongside physical media for individual ideation and documentation as well. Students now carry digital cameras with them, increasingly in the form of camera phones, keeping the full collection of photographs on their computer or on the web, and printing and pasting the most important photographs into their Idea Logs. Interactive prototypes and written documents are also created on the computer, based on sketches and notes in the log.

1.2 Overview

In this paper, we explore some of the cultural and practical issues that arise when deploying technology in design environments. We give an overview of the culture and theory behind design education. Next, we present study methodologies for deployments of technology hybrids to design classes and analyze students' use of the iDeas tools. We find that notebook entries tend to happen on weekdays outside of class, and that the prevalence of students' graphical annotations seems to correlate with their class performance. Furthermore, we discuss possible reasons for differential adoption patterns and the emergence of hybrid complementary versions of the Idea Logs. We conclude with implications for future research.

2. IDEAS LEARNING ECOLOGY

To research how integrated interactions might influence the culture of design, we are developing the *iDeas learning ecology*. The goal of the iDeas project is to fluidly integrate physical and digital technologies to support design education. In this paper, we discuss studies of augmenting one central artifact of current design practice: the Idea Log.

2.1 Capture

The iDeas learning ecology supports the capture and storage of handwritten notes and digital images. To capture written content, design students use the Anoto digital pen system [2]. (For the study deployments, we used Nokia SU-1B [34] and Logitech io2 [27] digital pens.) When used with an Anoto digital notebook, the pens track on which page and where on a page writing occurs, as well as the current date and time of each stroke. Users may upload and view their digitized notes by synchronizing with a PC. Unlike purely digital systems, the Anoto digital pens also act as normal ballpoint pens: should the pen digitizer fail (*e.g.*, if the pen runs out of battery power), users may continue taking notes and sketching as if they were writing with normal pen and paper. Likewise, if the physical notebook is lost or unavailable for any reason, users may refer to the electronic version of their notes.

The iDeas system does not specify a particular interface for capturing digital images, instead allowing users to import digital images from anywhere. Designers may document ethnographic studies using digital cameras, take quick snapshots of serendipitous moments using camera phones, or find inspiration in images downloaded from the web; all of these may be imported into the iDeas ecology.

2.2 Browsing

One component of the iDeas learning ecology is the ButterflyNet browser [48], which takes advantage of digital content and metadata (*e.g.*, timestamps) to offer a rich interface for visualizing notebook contents and images (see Figure 3). Notebook pages currently in focus are displayed in the *content panel* on the left; the browser offers the ability to zoom in or out and display multiple pages at a time via a drop-down menu. The *context panel* on the right automatically presents data related to the pages in focus, such as images taken around the time the page was written.

At the top of the browser, a *timeline visualization* allows users to jump to content by date. The height of each bar represents the amount of content written on a given date. Flags representing course milestones, indexed by date, provide links to course web

pages while simultaneously providing a visual aid for students searching for content related to a given milestone. Users can also easily export notebook pages as images to other programs. This allows them to complete common tasks such as pasting sketches into documents or sharing their design content through email without the burden of scanning.

3. EVALUATION

The focus of our studies has been to begin to understand the culture and practices of students through the apprenticeship process of becoming designers. In order to scaffold student learning, we are interested in knowing what design students do, and when and how they do it. We have conducted two longitudinal studies of the use of iDeas in design education. For these studies, we have instrumented ButterflyNet with interaction logging capabilities in order to track users' activities with the browser and their digital content.

The first study ran during the ten-week fall quarter of 2005, when we deployed parts of the iDeas ecology to selected sections of the undergraduate introductory HCI design course at our university. The following winter quarter we ran the second evaluation, deploying iDeas to all students enrolled in the HCI Design Studio course at our university. We chose these courses as both have a focus on collaborative project work. Moreover, both courses employ the studio critique method for formative assessments.

During both quarters, we conducted evaluations through four methods: *observations* in class and videotaped of group meetings; *logs* of activities within the iDeas ecology and some electronic exchanges across groups; *analysis* of the students' Idea Logs, associated coursework, and performance metrics; and *pre- and post-experience questionnaires* measuring attitudinal, self-reported behaviors, and experiences within the groups. In particular, students were asked about their group dynamics, design practices and note taking strategies in the course, as well as their assessments of the iDeas software and Anoto pen hardware.

In addition to how the iDeas learning ecology may change practice, this system is also a powerful instrument for studying design students. Digitally augmenting paper lowers the threshold for acquiring aggregate metrics of notebook activity, timestamped ink strokes enable researchers to ask finer-grained questions, and a digital dual allows researchers to examine content without taking the notebooks away from the students.

3.1 Study 1: Introduction to HCI Design

For our first study two sections of the introductory HCI course were randomly selected to participate with a total of 30 students (23 male, 7 female). The 30 students comprised a diverse background of ages, departments, majors, years in school, and ethnicities. Students formed teams of three or four students to pursue a quarter-long project, during which they designed, prototyped, evaluated, and refined an interactive system. Project topics were determined by each group; examples included accessing text-based voicemail on handhelds, clothing assistants, and bus route helpers, among others. The Idea Log recorded individual students' design work on the project and class in general, and were maintained throughout the quarter.

Eighteen students in one discussion section of the course were provided with Anoto digital pens, corresponding A5-size notebooks (148 mm × 210 mm), and an initial version of the iDeas learning ecology for archiving and browsing their notes and images electronically. Twelve students from a second discussion section were recruited as control subjects. These students did their coursework in the traditional fashion with other students in the class, using normal paper notebooks and pens for their Idea Logs.

We videotaped group meetings from three student teams; we also collected email and instant messaging communications from one of these groups. Figure 1 shows one such meeting, where students are interacting with their multiple computing devices and each other. This data should help in determining some of the factors of successful groups negotiating the interweaving of social and cognitive factors involved in establishing a joint problem solving space [4].

3.2 Study 2: HCI Design Studio

For the second study, all 48 students enrolled in the HCI Design Studio course during winter quarter were asked to participate in

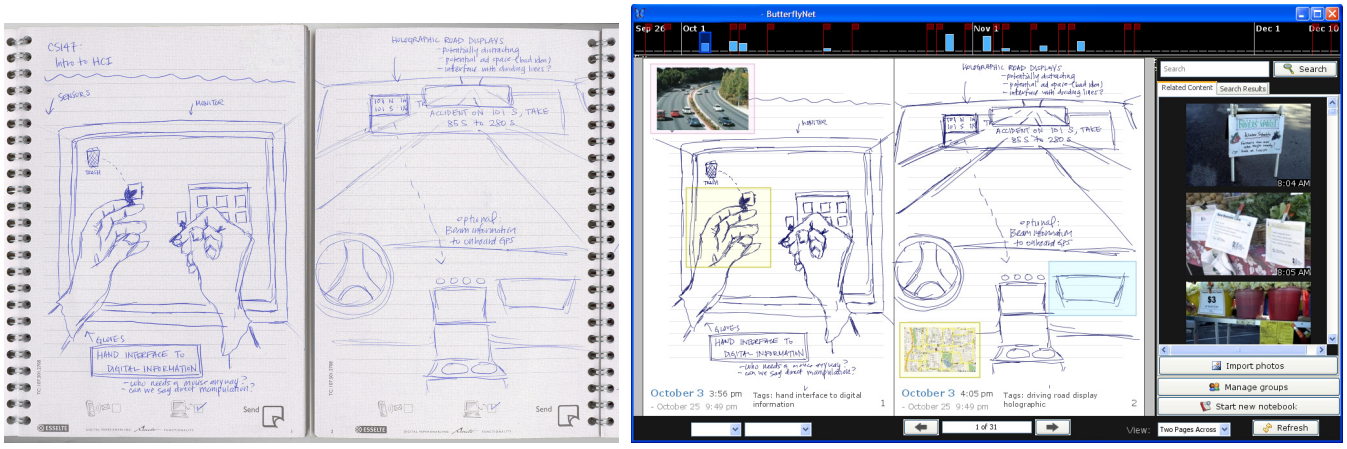

Figure 3. *Left*: Pages 1 and 2 from a student's Idea Log. *Right:* The same pages viewed in the ButterflyNet browser. Notebook pages and annotations are presented in the left-hand content panel, while contextual data (*e.g.*, related images, search results) is presented in the right-hand panel. Above, a timeline shows class milestones along with a bar graph visualization of the amount of notes collected on days throughout the quarter. (Note that the digital view is not possible using the physical notebook, as the sketches are physically on opposite sides of the same piece of paper.)

Figure 4. Students on a field trip recording observations and interviews in their Idea Logs with the Anoto pen. (Study 2)

the evaluation of the next version of the iDeas learning ecology. Of these, 47 (10 female, 37 male) agreed and were provided with Anoto digital pens, and notebooks (137 mm × 203 mm). Four students (2 males, 2 females) had used the pens through participation in the first study. Participants were predominantly engineering students, the majority pursuing degrees in Computer Science and Symbolic Systems. Participants were evenly split between undergraduate and graduate programs.

In this course, students participate in several groups throughout the quarter, as the four project assignments include individual turn-ins and group deliverables. Sometimes they are grouped in dyads and other times in groups of up to four students. For example, observations are often done individually, within the context of a larger group, as when the class took a field trip to practice contextual inquiry skills at farmer's markets (see Figure 4). In contrast, the final project emphasizes testing and iteration of a functioning interactive prototype and is organized for groups of four students.

3.3 Sharing

Initially, the iDeas software did not have any direct collaboration features. Users could only view their own digitally captured notes, though they could then export their sketches and writing to other applications, such as word processors and email clients, and share through other channels.

For the second study, in response to observations and user feedback, we added several networked collaboration features to the iDeas learning ecology. Users now have the ability to create, join, and leave groups. Members of a group can directly view the notebook pages of other users in the group electronically through the ButterflyNet browser.

We also added tags (text labels of pages) and annotations (text or image labels of page areas) to the system. Group members can comment on each other's work via highlighting and annotating interesting or noteworthy pages. These tags and annotations are indexed and searchable for easy retrieval at a later date.

Finally, we added the concept of staff members, who act as administrators in the iDeas system. Staff members have access to aggregate views of the entire class, as well as the ability to view and annotate any student's notebook.

4. RESULTS

The iDeas learning ecology has proven invaluable as an instrument for studying design students: we have gathered extensive data on design activity and notebook usage. Through the questionnaires we have also learned of their opinions about the system and their feedback on the iDeas implementation, as well as their reported behaviors in groups and with respect to multiple media sources.

4.1 Study 1: Introduction to HCI Design

In the first study, project grades across all sections for the class were evenly distributed; we did not find any undue bias or influence on performance due to introduction of the iDeas software or the Anoto pen. Grades in the experimental section and in all sections of the course were consistent with other years' distributions.

In the post-experience questionnaire, participants rated the iDeas system as significantly useful, easy to understand, and easy to learn (median 4, 5-point scale). Students preferred using iDeas to export and share their design content over traditional means of doing so such as copiers and scanners (median 6 in a 7-point scale). Several students commented that the ability to quickly and fluidly share notebook content (via exporting it to word processors or email applications) was valuable, and asked for more direct ways to do so. The browser's capacity to display multiple pages, visualize a timeline of when pages were created, and view pages within a calendar were also cited as useful.

4.1.1 Idea Logs

We have analyzed both the server-logged *timestamp data* for the 18 students that participated in the experimental section, and the

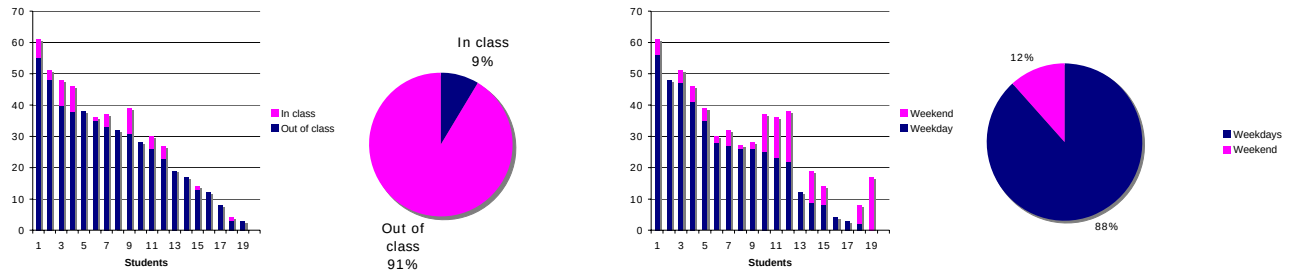

Figure 5. *Left:* Graph and pie chart of notebook pages written inside and outside of class in Study 1. *Right:* Graph and pie chart of notebook pages written on weekdays and weekends during Study 1.

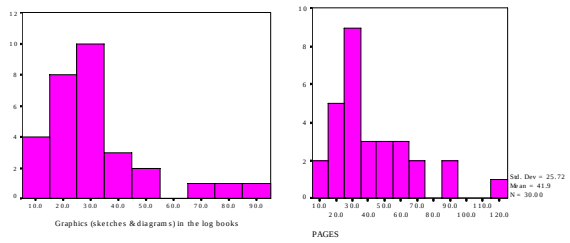

Figure 6. *Left:* Histogram of the number of graphics in students' log books in Study 1. *Right:* Histogram of the number of pages written in students' log books during Study 1.

content of the Idea Logs for all 30 students in both sections. In the experimental section, students readily adopted the technology, filling on average 33 full pages each on their notebooks, with one student writing as many as 68 pages, despite the added weight and encumbrance of the batteries and technology in the pen. The reader should note that current Anoto pens are bulkier than standard pens. We were interested in observing if this inhibited use.

Students found the benefits provided by the iDeas system to outweigh the challenges of adoption, as expressed in their post-experience questionnaire. Analyzing the content of the Idea Logs, we found that students used the system for note-taking in other classes as well, from Italian to optics and economics. Students in the control section covered significantly more pages in their log books than those in the experimental section (54 to 33 full pages on average); however, these additional pages did not have an effect on the students' course performance. There was no significant difference in the course grade distribution between the experimental and control sections. We discuss possible reasons for this discrepancy in the Discussion section of this paper.

The 18 students in the iDeas section of the study authored a total of 550 pages, the majority of which were completed outside of class during weekdays, as Figure 5 shows. Approximately 2.4 pages per student were written during class, and 25 pages per student outside of class. 5.7 pages were written in during weekends throughout the quarter, contrasting with the weekday average of 22.1 pages.

Two coders (the first two authors) working independently analyzed the Idea Logs for their graphical content, counting an average of 32 sketches and diagrams during the seventy days of the quarter across both sections. While the class does not require or favor students' graphical abilities, some students had as many as 92 sketches and diagrams, and no student had fewer than 11. Participants in the control section created slightly more sketches and diagrams than those in the experimental section, an average of 36.6 to 28.5 graphics per student, but this difference was not statistically significant (see Figure 6).

4.2 Study 2: HCI Design Studio

Of the 47 students that received pens, 40 uploaded data, and it is from those students that the data below is drawn. Of 40 active users of the browser, nine synchronized their pen and notebook data in the final week of the study, 12 in the final two weeks, and nine in the final month.

4.2.1 Idea Logs

Through the logging features in the iDeas browser we have realized that this class of designers-in-training has taken to the iDeas technology. It is also worth noting that the iDeas ecology performed well out in the field, during contextual inquiring undertaken by the students. In the fifty days of the study, the students entered a total of 3,592 pages in the iDeas system. The class as a whole wrote an average of 56 pages each day.

Students vary greatly in the frequency and amount with which they write into their Idea Logs, as the histogram of Figure 8 shows. Each student contributed approximately 1.4 pages per day, averaging between 76 to 86 pages each, with one student writing as many as 267 pages (an average of 5.34 pages per day), and none writing less than twelve pages. Students wrote on average, 10.48 pages over the weekends for the time period under consideration, as Figure 7 shows. Even during their field trip outing, despite adverse conditions (taking notes while standing in the rain), students wrote an average of 4.27 pages.

Regardless of the fact that both courses make class handouts and presentations available online, students in the second course wrote significantly more pages during class. On average, students wrote 20 pages during classtime over the fifty days under consideration, leading to a per-class average of 1.4 pages per student. In contrast, students wrote on average 67 pages outside of class, as Figure 7 shows.

5. DISCUSSION

In this section, we reflect on the results of the two studies, and draw out the salient benefits of the system (user enthusiasm, increased ease of incorporating sketches into later design documents, an integrated repository for sketches and photographs), shortcomings discovered in the first study that led to feature introductions for the second (support for sharing content with teammates), and barriers that persisted across both studies (most notably, that the multiple failure points of the

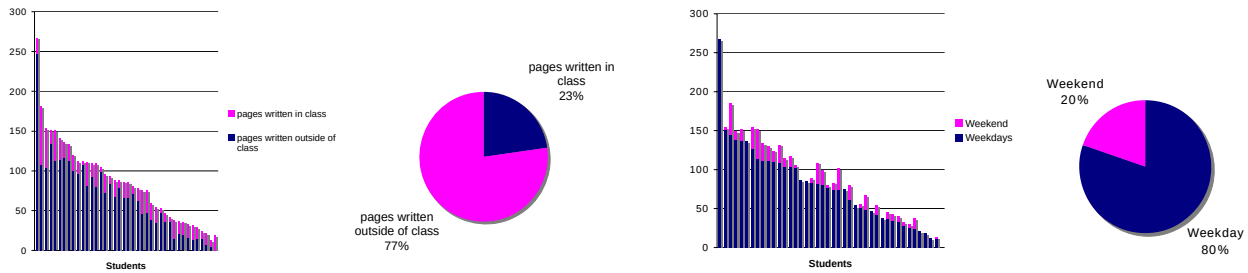

Figure 7. *Left:* Graph and pie chart of notebook pages written inside and outside of class in Study 2. *Right:* Graph and pie chart of notebook pages written on weekdays and weekends during Study 2.

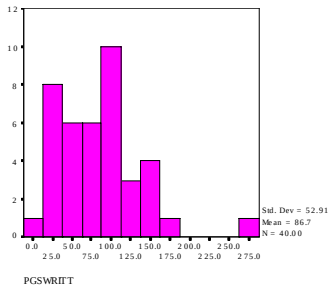

Figure 8. Histogram of the number of pages written in students' log books during Study 2.

infrastructure discourage use).

5.1 Barriers

In both quarters, a small minority of students did not continue using the technology after the initial novelty wore off. In the coming section, we identify the possible causes for this lack of continued involvement, and consider the data evidence for clues to support each of these. We then discuss intriguing findings in the differences between the physical and virtual notebooks students maintained.

There were several barriers to adoption of the iDeas system that emerged during the course of the studies. Perhaps the most significant constraint was the pen itself. While somewhat ergonomic in its design, the Anoto digital pens were sometimes described as big, clunky, and awkward, leading some users to not carry them around as frequently. Several users cited battery life as an issue; having to remember to charge the pens every day was a maintenance cost for study participants. While the heavy use the pens received during the studies corroborates other studies of the Anoto pen (*e.g.*, [48]) in downplaying these as serious concerns in user tests, the size, girth, and weight of the Anoto pens have proven to be serious barriers to adoption among consumers. We consider the Anoto pen to be a research prototype, but for longitudinal deployments of current technology hybrids, such issues must be taken seriously.

The Anoto digital notebooks also drew some complaints. Most notably, from conversations with some students and teaching assistants, it appears that lined notebooks encourage textual content and discourage freeform content. This was a design detail we had not considered prior to the study, and we handed out lined notebooks because that was the only available option preprinted with the Anoto pattern. Given that most design sketchbooks are unlined, we plan on making unlined Anoto sketchbooks for future deployments.

Finally, several users had difficulties with software installation. In the current implementation of iDeas, users were forced to install software components from both Anoto and the pen manufacturer in addition to the ButterflyNet software, leading to a system with several potential points of failure. Again, these issues, while not important in a short-term user study, are very real concerns for a longitudinal deployment.

5.2 Putting the Barriers in Context

The barriers mentioned above could help explain the significant difference between the pages written in for the first study. Students in the control section of study 1 wrote on average 54 pages to the 33 pages per student in the experimental section. In this section, we analyze the possible reasons for this page difference and highlight further avenues for research.

The first explanation we found is that part of this difference in page quantity could be related to the time that the control section had a chance to browse through and review Idea Logs from previous years, while the experimental section did not get to see these. Unlike controlled experiments in labs, we made the choice to study the use of Idea Logs in their natural setting, prioritizing authenticity of the results over complete control of the experimental conditions. We believe this real-world user study and evaluation of the tools over the quarter will produce richer and more relevant results than a laboratory analysis.

Despite this unequal exposure, the differences in page quantity deserve closer attention. We are very interested in understanding and overcoming the challenges that iDeas poses for design students, and have begun to analyze the data keeping in mind the barriers mentioned above: the digital pen form-factors, the lined notebooks, and the occasional difficulties with the ButterflyNet software. Below we address each of these potential barriers and evaluate the likelihood that they influenced the students' writing.

To determine whether the digital pen was responsible for the relatively larger number of pages in the control section in study 1, we compared the number of pages written in the notebook to the number of pages synchronized. The difference—33 pages written to 27 synchronized—was not statistically significant. Moreover, the abundance of page data from study 2 seems to indicate that students have no problems using the pens themselves given the advantages of the system.

Similarly, we considered whether lined notebook pages may have played a part in the differences of written pages across sections. This viable hypothesis was not proven during our studies, and cannot be held accountable for the page difference across sections, as only three students in the control section used unlined notebooks and their Idea Log content did not significantly vary with others.

We evaluated each of the barriers identified by students and staff, and found that they had little or no influence in the page difference. We have considered the influence of exposure to Idea Logs, yet we have not considered any effects due to iDeas. A possible explanation is that students in the pen section in study 1 saw less of a need to document the same materials as their teammates, leading to a reduction in overall redundancy, given the ease of sharing digital content. We are evaluating taxonomies and classification schemas to analyze the content of the Idea Logs to much higher detail in order to test this theory. Simultaneously, we have incorporated tools in the iDeas system to record sharing and editing behaviors, such that we may track the evolution of designs across teammates.

Conversely, it may be that the pen form factor was the primary factor in explaining this page difference, and that the abundance of pages in our second study is related to the students' expertise. As students progress through their learning process towards becoming expert designers they use the tools differently. The apprenticeship process by which novices learn to master the language and tools of a practice, well-documented in the education field [24], may be one of the reasons why students in the second study wrote in so many pages despite the pen's form factor interference. To study this possibility, we plan on

interviewing the students that have used the system who were included in the experimental session in the first study and participated in the second study. We are also exploring possible connections with other design courses instructors, across disciplines, to determine if their use of Idea Logs differs from the student population and explore collaboration possibilities.

Lastly, it is worth discussing the appropriateness of analyzing page numbers and content given that there was a small and non-significance correlation between the students' performance in the class and their Idea Log entries during study 1. We should note that the course in study 1 was a large, lecture-based undergraduate course where the Idea Logs were peripheral (6% of the grade). In contrast, the course in study 2 was a medium-sized, studio-based course comprising seniors and Master's students where the notebooks were central (30% of the grade).

Even though further analysis of the data from study 1 revealed that the quantity of graphical content in the students' Idea Log correlated with the students' performance in the course (Pearson r = 0.35, 12% of variance, non significant medium-strength correlation). The data from the second study may clarify the relationship between each student's Idea Log and their overall course performance, in particular concerning the relationship between graphics and performance. We are looking forward to unveiling what other abilities or proclivities the quantity of graphical content in Idea Logs may be standing proxy for.

5.3 Coexistence of Physical and Digital

A result mandated by the iDeas system is the practice of maintaining two complementary versions of their Idea Log, prevalent among the students in the experiment. We mention earlier that in the first study students entered 18% more pages, on average, in their physical notebook than in the virtual notebook. We seek to understand whether these physical-only pages are results of convenience (not having the Anoto pen when needed) or whether there are certain design activities that students considered better fits for each medium.

Is the canonical notebook representation the physical or the digital one? The findings are complex: in analyzing the notebooks from the second study we have found that students tend to paste in images to both their digital and physical notebooks, creating two disjointed complementary versions of their Idea Logs, one with digital extras and one with physical extras. For example, in the second study, a total of 193 images have been pasted in to the *digital* notebooks over a 50 day period, contributed by seventeen distinct users. Pasting in inspirational images or relevant materials is common practice for designers and it is encouraging to see students adopt such hallmarks of designer culture during their apprenticeship process.

Digital images played a major role in the design process of students in the second study, unlike in the first study, when students reported taking only one or two photos over the entire quarter (drawn from the post-experience questionnaire). A rich source of digital images related to the course has been the photo sharing site Flickr [47]. In addition to the course staff and mentors, fourteen students contributed 372 images to this photo sharing site, at an average of 26.5 photos per student, during the fifty days under evaluation.

The coexistence of multiple and competing media, with complementary materials pasted into the physical notebook while digital references are inserted into the virtual one, opens a field ripe for analysis: which one is the "real" notebook? The answer may vary for each student, and we will be analyzing both the physical and digital instantiations of the notebooks, as well as querying each student for his or her perceptions.

6. DESIGN IMPLICATIONS

These two studies of the iDeas learning ecology have produced several insights, both theoretical and practical. In this section, we identify guidelines for development and possible directions for future research into augmented paper interactions for collaborative creative work.

6.1 Tensions between Digital and Physical

One challenge that figured prominently into our deployment of hybrid physical and digital technologies is the tension in managing multiple representations of data. As noted earlier, design students already make frequent use of digital cameras for their still image and video capture capabilities, which produce digital content. Current practice for dealing with digital images is to print out and paste selected images into the Idea Log, meaning that only "important" images make it into the physical notebook, as the insertion process is time-consuming.

With the hybrid notebook affordances offered by the iDeas system, an interesting situation arises: the introduction of digital affordances into the traditionally physical design notebook creates a situation in which both the physical world and the digital world contain parts of the notebook not present in the other half. In general, the system results in three classes of data: content that exists both in the physical and digital world (*e.g.*, ink strokes captured by the Anoto pen); digital-only content (*e.g.*, digital pictures, annotations, hyperlinks); and physical-only artifacts (*e.g.*, magazine pages, newspaper clippings, non-Anoto paper). Devising how best to handle these exchanges and transport or duplicate information across boundaries will be a defining challenge for the field of human-computer interaction in coming years.

6.2 Impact on Current Practice

Integration of physical and digital interactions definitely had some encouraging influences on practice. While examining students' project reports, we noticed that several groups had inserted sketches from their Idea Logs into their reports as samples of their ideation, a practice that was not prevalent in previous editions of the courses. The ability to quickly and fluidly insert excerpts from paper notebooks into digital documents has been repeatedly cited as a positive feature of the iDeas system. At the same time, our observations lead us to conclude that integrated systems need to introduce plenty of novel digital affordances to compensate for any losses of flexibility that arise from integration with digital technologies. How to measure the potential of new interactions while facing the costs imposed by using nascent or experimental implementations is one of the biggest challenges of doing longitudinal studies on emerging technologies.

Another lesson we gleaned from our deployments is the importance of fitting into *existing digital practices* wherever possible. One common practice among current students is photo-sharing on websites such as Flickr [47]. Importing photos into

iDeas thus meant that students had the additional burden of maintaining two distinct image repositories. We plan to take advantage of Flickr's photo sharing and annotation capabilities by using the Flickr website as our photo store and integrating Flickr into the iDeas learning ecology. In the era of digital ubiquity and the service-oriented Web, we foresee *mash-up programming* playing an important role in the integration of people's physical and digital practices.

6.3 Models of Sharing

Introducing electronic collaboration features into design notebooks elicited some interesting questions regarding sharing. In a traditional Idea Log, design content is difficult to share unless the physical log is present; the notebook is a highly personal artifact. With an electronic, networked Idea Log, sharing is no longer limited to collocated activities. One obvious area of consequence is privacy. Some students requested privacy features (*e.g.*, "do not share this page"); others were concerned that timestamp data might be using against them during grading. In constructing systems which introduce digital affordances into traditionally physical systems, designers should take into consideration existing modes of collaboration and sharing.

Another potential area of research is facilitating new models of sharing, such as group notebooks. A group notebook could serve as an intermediate level of sharing, a type of collaborative filter: students could put important content from their personal Idea Logs or elsewhere into the shared notebook. Such new affordances could have benefits for students and instructors, *e.g.*, by serving as an informal bookmark and presentation mechanism for students which instructors may then examine.

6.4 Rich Capture

One of the most powerful aspects of physical and digital technology hybrids is rich capture. Digital capture of pen strokes means that notebook content is digitized, and thus viewable by others, more quickly. Digital technologies also offer the ability to capture additional metadata, including timestamps of notebook pages and photographs.

This rich capture of design activity offers a number of benefits to interested parties. Students now have their notebooks indexed by time ("What did I write last Saturday at the museum?") and can see images taken around the same time as their written notes. They can also view other group members' content in the same fashion. Instructors can now see a gestalt of students' notebook activity or view specific notebooks without collecting Idea Logs from the entire class, just by opening up the ButterflyNet browser.

Finally, rich capture offers researchers insights into captured activity not easily duplicated by other means. Questions such as "Do students mostly write in their notebooks immediately before deadlines?" can now be analyzed qualitatively, while more abstract questions such as "What is the lifecycle of a sketched idea?" or "How are ideas shared?" can be investigated more deeply. We plan to explore further uses of this powerful microscope into design education and practice.

7. RELATED WORK

This research draws from prior work in three main areas: augmented paper interfaces and physical-digital hybrids, sketch-based tools, and tools for education.

7.1 Augmented Paper Interfaces

There is a growing body of research on systems that make use of both physical and digital interfaces, and augmented paper interfaces in particular. Mackay's studies of paper flight strips [29] and biology laboratory notebooks [30] showed the viability and importance of taking advantage of human abilities and current physical practices when designing new technologies [12, 20].

Other research has developed and tested applications that integrate physical and digital interactions. Stifelman's Audio Notebook [44] introduced a paper notebook augmented with audio feedback; tapping on a portion of a handwritten page retrieved audio recorded at the time those notes were written, an early example of using paper as a query interface. Books with Voices [19] demonstrated a similar concept, using paper transcripts as an interface for browsing the corresponding video. Designers' Outpost [21] and Rasa [31] augmented existing paper-based work practices by directly integrating physical and digital interactions through computer vision and tracking. NotePals [11] first introduced the idea of shared electronic repositories for paper-based notebooks. Paper PDA [18] and PADD [16] allowed users to take advantage of electronic capabilities while using paper via synchronization. ButterflyNet [48] integrated paper notes and digital photographs into a capture and access system for heterogeneous media.

The iDeas learning ecology extends this prior work by introducing affordances for sharing, visualization, and annotation of heterogeneous content in a collaborative context. Additionally, while several of these systems have been evaluated in short-term usability studies, none of them have attempted to evaluate integrated interactions longitudinally.

7.2 Sketch-Based Tools

Traditionally, interactive systems have addressed the processing and manipulation of "structured" content: word processing, email, web browsing, etc. Learning technologies — from graphing calculators to electronic portfolios [6]—have generally followed this trend, with some exceptions in the area of design. SILK [23] and DENIM [26] are informal sketch-based tools for low-fidelity user interface prototyping. DEMAIS [3] is a sketch-based storyboarding tool for multimedia design. Classroom Presenter [1] studied digital ink and tablet PCs in university lectures. In general, however, learning tools for the creative production of sketch-based content have not been studied extensively.

7.3 Tools for Education

Within the US, several companies and districts (Edison Schools, Illinois' School District 203, and the State of Maine, among others) are already supplying every student within their middle- and high-school classrooms with laptops or handheld computers. Colleges (most notably Duke in 2004) are presenting the incoming freshman classes with iPods. The integration of these technologies to the curriculum varies from little relationship to a strong dependency, yet few projects concentrate on fostering the students' learning through groupwork, and even fewer involve technological innovations. Commercial applications focus primarily on the needs of school districts, administrators and teachers, and while collaborative learning is seen as the preferred knowledge acquisition modality [33], many innovations

concentrate on providing better access to traditional lectures (*e.g.*, [1, 5]).

Concentrating precisely on the inquiry-driven learning and collaborative groupwork, Pea and Maldonado [36] review the latest applications that support for what they term wireless interactive learning devices (WILD). From iPods to handhelds, from blogging on the phone to probe-based chemistry, they group innovations by their application, rather than their technological platform. Their taxonomy of WILD comprises five categories: 1) augmenting physical space with information exchanges (*e.g.*, [7, 9, 46]); 2) leveraging topological space (*e.g.*, [14, 28, 39, 40, 42]); 3) aggregating coherently across all students participating individually (*e.g.*, [10, 37-39]); 4) conducting classroom performances (*e.g.*, [15, 41]); and 5) enabling act becomes artifact (*e.g.*, WHIRL [38]). The iDeas ecology falls into the second category (leveraging topological space) for its fluid transitions between physical and digital representations, and the fifth category (act becomes artifact) for its reflective use of the Idea Logs as formative assessment tools.

8. CONCLUSIONS AND FUTURE WORK

This paper has contributed two longitudinal studies of an augmented paper system — the iDeas learning ecology — in the context of design education. This is the first time a longitudinal study of this class of interface has appeared in the literature. Data was collected through observations, server logs, content analysis of notebooks, and questionnaires. These studies found the salient benefits of the system to be user enthusiasm, increased ease of incorporating sketches into later design documents, and an integrated repository for sketches and photographs. We used shortcomings discovered in the first study to drive feature introductions for the second, most notably support for sharing content with teammates. Additionally, there were significant barriers to use that persisted across both studies, most notably that the multiple failure points of the infrastructure discourage use. These barriers highlight the challenges of achieving ecological validity in ubiquitous computing. Augmented paper interactions for designers work best as calm technology [21], yet research prototypes, almost by definition, are more brittle, and less calm, than a production system might be. We suggest that longitudinal studies still have significant import in emerging domains, but that the un-calmness of prototypes may depress usage.

Looking forward, the key area we see to increasing the utility of the iDeas learning ecology is extending the system to integrate additional design artifacts, including walls and whiteboards (prominent physical tools in the traditional designer's arsenal) and mobile devices (increasingly digital parts of everyday life). We also plan to investigate the evolution of the designer's information ecology. As digital tools and hybrid technologies continue to become more commonplace in design, they will undoubtedly have an effect on how designers capture, organize, manage, and present their content. Possibilities include adding shared intermediate representations or ambient awareness of design team activity. Finally, we plan to study the use of sharing in more detail. While the version of iDeas deployed in the second study had sharing capabilities, we did not instrument the system to log or measure sharing activities.

The iDeas software is open source, and is available at http://hci.stanford.edu/ideas.

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