Identification of patterns of tool use and sketching practices in a *learning by design* task

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Abstract: The complex interaction of tool use (both physical and digital) in face-to-face collaborative learning situations, and the role that these tools play in facilitating group work is increasingly important as tools for learning become more sophisticated and specialized. In this paper, a group of five high school students is studied as they engage in a *learning by design* task to design an educational resource about a local waterway. They carried out this design work in The Design Studio at the University of Sydney, using an iPad projected onto a whiteboard wall. Multiple streams of data were collected, visualized and analyzed, which allowed the overall patterns of tool use for all members of the group to be identified in relation to the development of their design. Two patterns of tool use are identified and analyzed according to the practice of sketching identified in other fields of design.

Introduction

As learners engage in more complex tasks, the ability to capture the processes of learning is increasingly challenging. This paper presents initial research into the combination of tools used by high school students during their design work in a dedicated design space. As part of a project funded by a regional government organization, a group of school students engaged in the design of a learning resource about a waterway of local significance, to be shared with other schools throughout the region. Students were observed and guided through a design process, intended to help them learn about issues relating to water quality in their area. Students did their design work in a physical space resourced with tools for educational designers. Many aspects of the processes of design are of importance to learning, particularly in *learning by design* tasks. As yet, these have not been discussed in the research literature. In this research, work on combinations of tool use in the process of learning in online environments, is aligned with knowledge of the importance of sketching in other areas of design, in order to identify patterns of productive activity in *learning by design* tasks.

The paper begins with a brief overview of research involving integrated tool use and the processes of collaboration (Thompson & Kelly, 2012a, 2012b; Zenios & Holmes, 2010; Thompson, Ashe, Carvalho, Goodyear, Kelly & Parisio, accepted), as well as background to *learning by design* (LBD), and the role of sketching during the design process. The physical and digital space in which the study was conducted will be described, as well as the participants and context of the LBD task. Multiple streams of data are then visualized and analyzed to describe the integrated, and specialized way in which students used and appropriated the tools available to them, for their purposes.

Literature Review

Much of the work examining the processes of learning during complex collaboration with regard to combinations of tool use, has been performed in online spaces (see for example Zenios & Holmes, 2010; Thompson & Kelly, 2012a; 2012b). These studies have examined the affordances of using a combination of online tools for discussion and idea development (such as chat or video conferencing tools), for the permanent recording of the progress of the group, and for in-depth investigation of a problem (such as wikis). In these studies, the permanence of the recording space (the wiki) was important for the progression of the collaboration; more complex discussions were able to take place once ideas were recorded. The recordings enabled participants to refer back to previous ideas. In work on face-to-face collaboration, Thompson et al. (accepted) have shown that differentiated tool use can be an indicator of successful collaboration, in a group, as students develop expertise in the role and tasks related to the tool used.

Analyzing the processes of learning in CSCL is important, in particular as the context of learning environments are able to be better described (Thompson et al., accepted). Work in this field has discussed this importance in terms of social interactions, analyzing the discourse, as well as non-verbal interaction (for a review of this, see Goodyear, Jones & Thompson, forthcoming). By extracting additional data from complex datasets, analysis of additional processes of learning can be added to our understanding of collaborative learning (Thompson et al., accepted; Kennedy-Clark & Thompson, accepted). This paper addresses the processes involved in *tool use* in a dedicated design space.

Design activity has been demonstrated to facilitate deep learning about complex systems (Hmelo, Holton, & Kolodner, 2000; Kolodner et al., 2003). The goal-orientation of design-based science learning, where

the content is fundamental to producing a working artifact, acts to contextualize the process of inquiry. "Design is used as a vehicle through which scientific knowledge is constructed and real-world problem-solving skills are cultivated. The design challenge provides impetus for identifying what needs to be learned and for sustaining engagement in inquiry over time, as well as providing need for cultivating and using a variety of skills." (Vattam & Kolodner, 2008, p. 407). Vattam and Kolodner (2008) describe LBD as internally driven by a "need to know" and a "need to do". During this iterative process students share experiences and ideas as they articulate what they will need to learn in order to successfully complete the design challenge. In describing this process they highlight the importance of the *design rule of thumb,* which assists learners to connect content and application.

The early conceptual phase of design is cognitively very demanding. During this phase, ideas are generated rapidly. Designers need to try out new ideas quickly and cheaply before committing to one for further development (McGown, Green, & Rodgers, 1998). During this process, the intentions of the designers are represented, or externalized, in the form of verbal explanations, written documents, sketches, drawings, diagrams, and sometimes as models. Free-hand sketches are an indispensible tool at this stage not only for externalizing design ideas in order to communicate with others, but also for examining the potential of a solution before further commitment. For designers, drawing is the act of exploration (Hokanson, 2008), of discovery (Berger, 2007), and an aid to their thought process (Buxton, 2007). Designers draw in order to spot problems, see new features and relations among elements, discover or promote new ideas, and refine current ideas (Suwa & Tversky, 2002).

The importance of sketching in design is not the sketch as a final product of design, but as a process that explores, questions, suggests, proposes, and provokes thoughts and ideas (Buxton, 2007). In other words, "sketching is thinking" (Goldschmidt, 1991, p. 130). This process enables the designer to find new aspects of the problem and to generate new ideas (Suwa, Gero, & Purcell, 2000). Designers from various fields rely on the use of visual representations as thinking tools in their design process. For example, Henderson (1999) quotes an engineer who stated "I can't think without my drawing board". Sketches can greatly improve communication in collaborative team situations (Eppler & Burkhard, 2006); they can be used to assist a group's reflection and communication process. This is because sketches and drawings bring the main features of the object of design to the conversation by making them explicit and thus debatable.

Methods

A group of 16 students and 11 adults participated in the project funded by a regional organization of councils, and supported by their high-school and a local environmental rehabilitation organization. The aim of the project was to develop an innovative fieldwork and multimedia framework to engage other students in water and land management issues. South Creek, the focus of the project has been described as the most degraded creek in the region. Threats to its health include vegetation clearance, urbanization and agriculture; resulting in concerns about increased nutrient levels and an increase in the number of weed species within the riparian zone. Over a number of months students and stakeholders participated in a multidisciplinary design process to create a learning resource for use in schools across the region. The students participated in planning sessions, a site visit, and a day of hands-on site restoration at the creek, before attending a *Design Day* at the University of Sydney.

The *Design Day* was an opportunity for the students to develop their ideas about the design of the educational resource, propose possible formats, identify constraints and generate a consensus upon which a brief for the multimedia designer could be written. Participants included expert learners (the students), who ranged in age from 12 to 17 years, and experts from education, environmental science and multimedia design. The *Design Day* began with each of the expert groups outlined their desires and constraints for the design of the educational resource, and these initial parameters were summarised and referred to during the rest of the day. In the Design Studio[(1)] participants were led through the first three stages of a design process: *empathize*, *define*, and *ideate* (following the Stanford University Institute of Design – An Introduction to Design Thinking[(2)]). The *empathize* stage took the form of a whole group brainstorming activity during which the initial desires and constraints were discussed and the critical components extracted. Participants worked in pairs for the *define* stage; each dyad performed a needs analysis to help define the resource. During the third stage, *ideate*, the participants worked in groups according to discipline area. One group contained all the adults including educators, multimedia designers and environmental scientists. The other three groups each included between five and six students – expert learners. During the *ideate* stage, participants were asked to generate ideas. They were asked not to limit themselves to their knowledge of technology and were instructed to record all ideas. The intention was to explore a wide solution space so that, later in the *Design Day*, these ideas could be distilled into one coherent solution and a brief presented to the multimedia designer for the creation of a resource prototype.

This paper follows one of the student groups during the *ideate* stage of the design day. There were five members of the group, three females and two males, whose ages ranged from 12 to 16. Video, audio and photographs of the collaborative design work were collected. Each group was given a choice regarding the digital tool they used (computer, interactive whiteboard, or iPad). This group chose to use an iPad that was

projected onto a wall painted in whiteboard paint (a 'white-wall', see Figure 1). Their interactions with both the physical tools (whiteboard/pens/erasers) and digital tools (iPad and projected screen) were recorded using video. In addition, two members of the group wore audio recorders, and photographs were taken every 12 seconds of the whitewall on which students were working.

Data describing the tool use, for each member of the group, in 30 second intervals was extracted from the video. The tool, action (writing or erasing), and location (inside or outside the projected area) were coded. The transcription of their discourse was analyzed in order to identify ideas important in the development of their design. These were then discussed and agreed upon by all authors of the paper in a group meeting (Thompson, Ashe, Yeoman & Parisio, accepted). In addition, the photographs of the whitewall taken every 12 seconds, were coded using The Collaborative Process Analysis Coding Scheme (CPACS) (Kennedy-Clark & Thompson, accepted). CPACS is a multi-level coding scheme that includes macro-levels (action and content) as well as micro-levels (pronouns, tense, modality, and attitude) of collaboration; only the macro-level code, *Content*, was used in this paper. The Content section of CPACS contains six codes: phatics (social – phatics, salutations, leave taking), planning, topic, task, tool use, and off-task. The photographs were coded by one researcher, and half were coded by a second researcher. Inter-rater reliability of 55% was achieved in the first instance, and 86% after further discussion. The ideas were plotted, over time, in combination with the tools used by each person and taking into account the *content* to which they were contributing. We used this visualization to determine patterns of tool use, and analysed the photographs taken of the whitewall from the perspective of sketching practices of designers.

Analysis

The design studio was equipped with a variety of design tools and participants were able to use them as they wished. This group of students was assigned to an area of the studio that had a white-wall (the entire wall set up as a whiteboard) an assortment of coloured marker pens and the ability to project either a desktop computer or a tablet computer, onto the wall (see Figure 3). They were also given blank paper and pens, sticky notes and various paper-based templates along with reference materials, which included maps and curricula resources. The students made no use of the paper-based tools; at no point did any of the group use, or even make reference to using, the paper-based resources provided. All activity revolved around the digital projection onto the white-wall; even the use of the physical marker pens was influenced by the projected image.

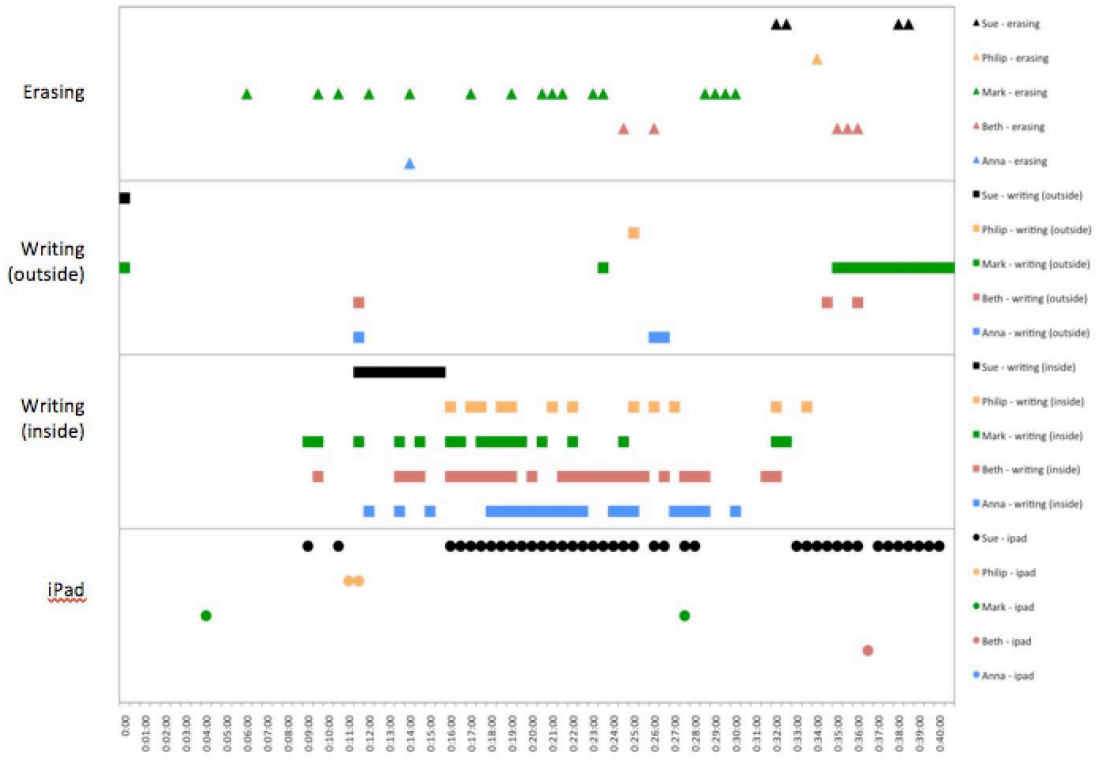

Figure 1. Tool use by participants over time

Figure 1 shows tool use during their collaborative design task. Each student is represented by a different color, and each section of the graph represents the use of a different tool. Circles, at the bottom, show the use of the iPad. Sue (black) was the main user of this tool. Other students had brief turns, Mark (green, 4, 27 minutes), Philip (yellow, 11 minutes) and Beth (red, 36 minutes). The next two sections on Figure 1 refer to writing on the

whitewall, inside and outside of the space illuminated by the iPad projection (Figure 3). All members of the group undertook this activity; there were periods of time when four of the five students were writing on the whitewall in the projected space simultaneously. Some work was performed outside the projected space, the most notable from about minute 34 by Mark (green). Finally, erasing activity is shown in Figure 1. While all members erased markings from the whitewall, Mark was primarily responsible for this activity.

Based on an analysis of the video recording, the session was divided into five phases; setup, briefing, design (I), technical problems, and design (II). Initially Sue requested that a computer (used by another group, operated via a wireless keyboard and mouse) be projected onto the whitewall. Her opinion was that the task would be simpler with a desktop system rather than an iPad. Sue took control of the computer keyboard in anticipation that the group would accept her request. When the group elected for the iPad to be projected, Sue relinquished control of the iPad to Mark. Sue soon asked Mark to hand her the iPad, which he did. During setup and briefing, the iPad was not used significantly; it was mostly used during the two design phases. In both of these phases Sue was, by far, the dominant user. During the task, there were only two minutes of the design work in which Sue relinquished the iPad; and during this time she was actively writing on the whitewall.

The students recorded their ideas by writing and drawing with both the physical marker pens on the whitewall and the digital pens on the iPad. These physical and digital tools were used in combination. Even though the entire wall was available, the students mainly confined their design work to an area formed by the projection of the iPad. As this space was relatively small, it became necessary to keep a record of what was written on the whitewall before erasing to make more space. Sue copied the text from the whitewall onto the iPad, making a permanent digital record of the writing. This text could be projected onto the whitewall, from the iPad, after the original had been erased. By taking control of the iPad, Sue effectively controlled the pace of the design task and also had some autonomy over which sections of the written text were preserved in digital form.

At various times, one or more students broke away from the accepted practice of writing within the projected area to build up an independent section on the whitewall. This could be regarded as a prototyping area, a place to sort out ideas before committing them to the projected area (and hence into the iPad), or as a method of rebelling against the group with ideas that had not been accepted.

Sue was an active member of the group. Once the task began, she took control of the iPad and dominated the creation of the digital artifact. Twice Sue relinquished the iPad; during the first, she became very active writing on the whitewall, effectively controlling the wall space, and the other was when the iPad had a technical fault. Sue stopped using the device when it was no longer being projected onto the whitewall. During this time, Sue did not use the iPad, however she did hold onto it, releasing it for technical assistance.

The use of the tools in relation to the development of ideas was visualized (Figure 2). Each photograph was also coded to illustrate any contributions the students made to the development of the *content* through writing, in addition to discourse. Figure 2 shows the ideas (the larger circles), with each individual idea represented by a horizontal line. Photographs of the whitewall were coded for the content of what was drawn, written and displayed. The CPACS *content* codes were phatics (x.1), tools (x.3), planning (x.5), topic (x.7) and task (x.9). Each person is represented by a different color, in addition to the five members shown in Figure 1, Steve, the facilitator, is also included.

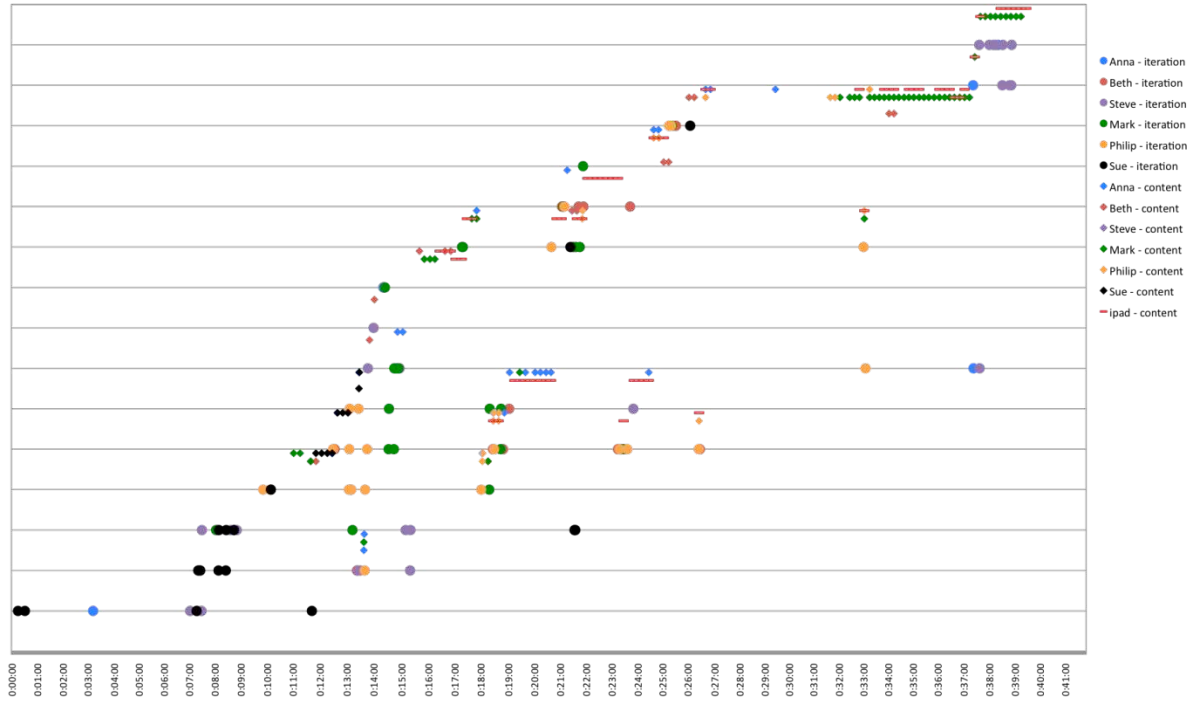

Figure 2. Additions made by participants during idea development, according to the content added over time

Figure 2 shows that the design process was not linear, that students often returned to earlier ideas and continued discussion. The whitewall was mostly used for recording information about the *task* and the *topic*, rather than for planning, phatics, or further reference to the tools. Often, the iPad was used just before a new idea was suggested; this could be because students were waiting for decisions to be recorded before they moved on. There are two occasions that were chosen for in-depth analysis of sketching practices due to the distinct patterns in students' use of the tools. The first, *collaboration*, occurs from 18 minutes to 23 minutes, when students simultaneously write on the whitewall while the iPad is also being used. It is at this time that they return to the ideas that were generated earlier in the collaboration. The second, *specialization*, occurs from 31 minutes to 37 minutes, when two members of the group dominate the use of two of the tools, for different purposes (Sue, with the iPad, focuses on the task, and Mark, on the whitewall, focuses on the topic).

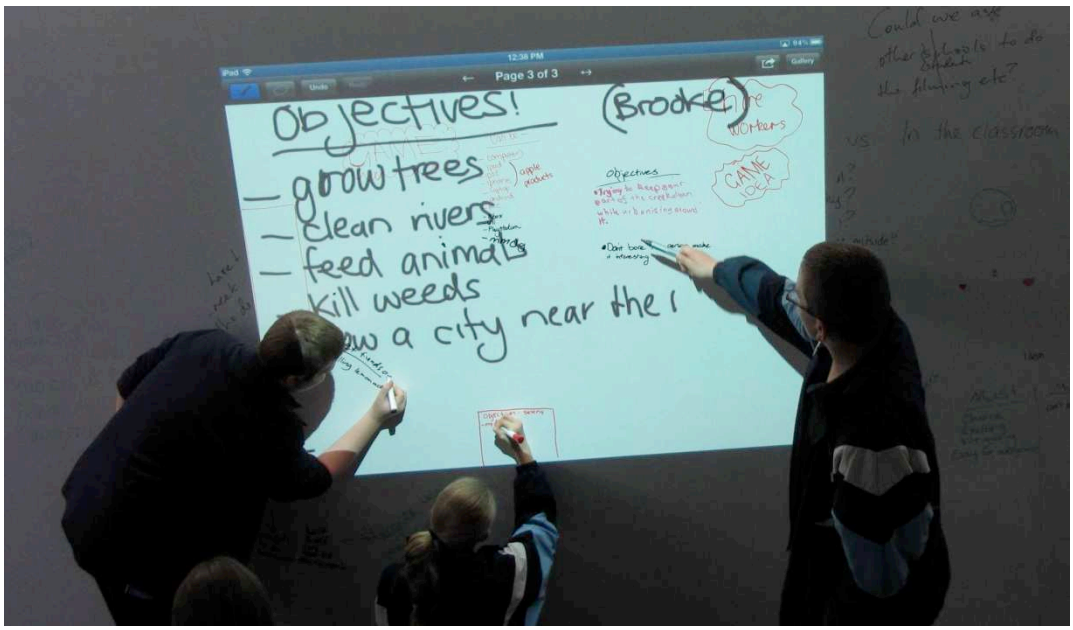

Figure 3: Collaboration

The *collaboration* analysis included an indepth analysis of 30 photographs, taken every 12 seconds (images 4248-4277). The students (shown in Figure 3) are collaborating to produce the 'objectives' for their idea of a game. It is notable that the students demonstrate behavior similar to practicing designers in many design fields. For example, the students use a variety of ways, using the available tools, to communicate their ideas to the other members of the team. Their verbal expressions are supported by drawings and text on the whitewall. This is similar to 'talking sketches' produced in the early stages of engineering design where ideas are exchanged and negotiated using sketches, text and diagrams (Ferguson, 1992). Visual representations, such as these drawings and marks on the whitewall, hold the design ideas stable so they can be argued and negotiated.

Students made several types of marks on the whiteboard during *collaboration*. A bulleted list of possible platforms for the game was produced, including computer, iPad, and Xbox. Some of the main ideas are written in capitals and enclosed by irregular shapes. Important terms and headings are underlined for emphasis. Groups of ideas, such as similar device types, are bracketed to illustrate similarities and relationships. At one point, lines were drawn across the bottom of the screen, projected on the wall, to symbolise the creek.

At this initial stage, ideas were still developing as they were being negotiated; some ideas were further developed and some were erased and replaced by new versions. For example, Phillip adds (and underlines) the words 'get funds' on the whiteboard. Beth develops the idea by adding 'selling lemonade' underneath. Phillip realizes that Beth has misunderstood the idea and continues with his line by adding 'off entrepreneurs'. The vagueness of the ideas and words on the whitewall does not seem to be an issue of concern for the students. In fact, it stimulates the conversation as the students try to make sense of the design task. This is a typical situation in most design fields where visual representations of ideas are initially vague and not fully explained but become clearer as the designers' thoughts progress (Hansen, 2000). The drawings and text on the whitewall have a fluid status. They represent ideas that are still changing. Sue is in control of the iPad and once an idea is relatively crystallized she commits the idea to digital ink, thereby giving the idea more permanence. After Sue copies the ideas onto the iPad, the other team members erase the text on the whiteboard wall.

Another similarity with typical design practices that this session demonstrates, is that drawings and marks on the whiteboard can be considered as either individually owned or as a shared entity (Eppler, 2007). For example, at one stage Anna decides to write her objectives for the game on the board by commandeering one section of the available space and drawing a line around it (see the lower, centre area of the projected image in Figure 3). She makes sure that the other students know that these are her ideas and they are not to be changed or erased. This is an example of individual ownership of a visual representation. The rest of the representations on the whiteboard are mostly shared where anyone can add to them; no one has declared their ownership.

This instance also shows how design representation can take both physical and digital formats (Eppler, 2007). This is clearly seen by observing how Sue records the team's ideas using the iPad, which is projected onto the wall, while the rest of the team draw and write on the whitewall with physical pens. The interplay between these two tools, the iPad and the whitewall, is worth noting. All of the team members are at once able to see the wall and what is being added to the iPad. They often comment on the text added to the iPad and even suggest more additions to the perceived permanent, master version residing on the iPad.

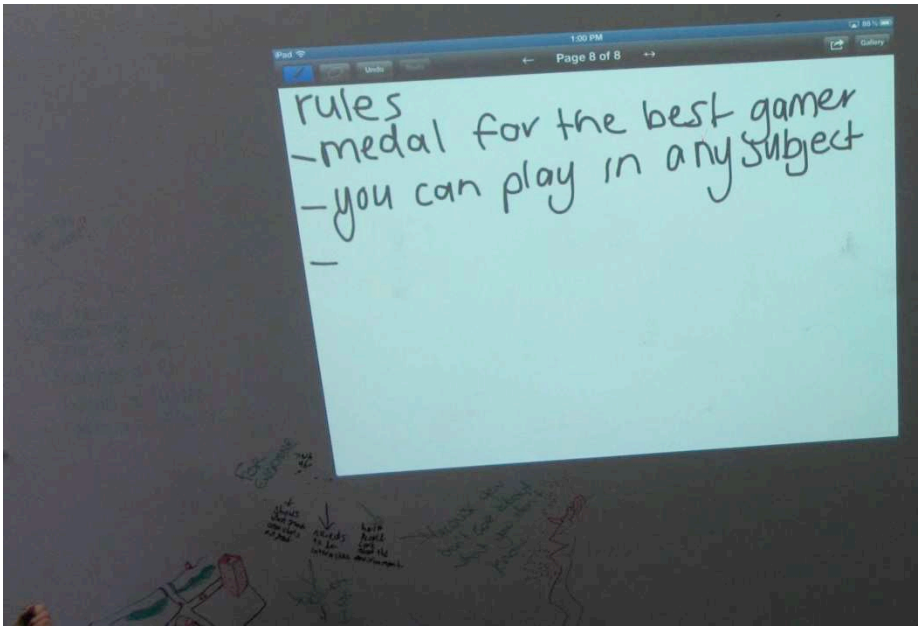

Figure 4: Specialization

Later in the session, the design needed to be finalized and a set of objectives put in place. This *specialization* session was analyzed using 25 images, taken every 12 seconds (4334-4359). Shown in Figure 4, ideas and representations on the whitewall were slowly erased as they were stored on the iPad. The idea of permanence given to the digital form is obvious here as the previously individually owned, and fiercely contested ideas on the wall are erased and replaced by the compiled list on the iPad. For example, Beth tried hard to protect her ideas written on the wall throughout the session. At one stage she proclaimed "*don't rub out my ideas*". Nevertheless, after Sue copied her ideas onto the iPad, Beth took the eraser and wiped the text from the whitewall herself. This is typical in most design areas where the initial sketches and representations are disposed of in favor of more formal representation of the design, often expressed in textual format (McGown, Green, & Rodgers, 1998).

While this sorting and storing stage was underway, Mark started drawing on the whitewall away from the collaborative area. Mark's drawings did not appear to be intended for sharing with the group since they were drawn outside of the screen area illuminated by the iPad projection. Mark was visualizing the previous ideas that he shared on the whitewall under the heading 'Objectives'. These ideas were about *"trying to keep your part of the creek clean while urbanising around it*". Mark visualized this idea by drawing a creek in blue pen with roads surrounding it in black pen. He also drew high-rise buildings in red and added grass areas in green. Mark did not share or discuss his drawings with anyone else. This seems to be an example of a 'thinking sketch' (Ferguson, 1992). Thinking sketches are often drawn by designers in order to better understand a situation and to develop personal ideas. Mark appears to be drawing for a similar purpose; he used the whitewall, away from the projected screen, because the drawing was not meant to be a permanent record; it was not intended for sharing with the group.

Conclusions

The collection of multiple streams of data allowed a detailed, multimodal analysis of the processes of collaboration. Visualisations of tool use, and design processes over time allowed the recognition of patterns, and directed the in-depth analysis of sketching practices of students. Students used the tools available to them in complex ways and for different purposes – they used the whitewall for ideas development and the iPad for recording in a more permanent way. The iPad became central to their collaboration. When the iPad failed, the group also ceased writing on the whitewall. Perhaps without the ability to create a permanent record, they were reluctant to move on, despite the availability of the whole wall. During the 40 minute collaborative design task, students developed expertise, and adopted specialized roles within the group. This was seen most clearly with Sue and Mark. Only one person could control the iPad at any one time; multiple people could use the white-wall simultaneously. Figure 1 shows significant overlap at the wall, with multiple people contributing to the task. This may indicate that the task was indeed collaborative in nature and that the use of the iPad was more pragmatic (to keep records of theideas) than an attempt to control the design task. All students were key in the development of ideas, demonstrated in their collaborative activity at the whitewall. The ownership of ideas was important, as was the requirement for a permanent record of them to exist.

This paper represents the initial analysis of a large data set, collected over several meetings. Future work will include analyzing the other groups who participated in the project, and tracking the development of their ideas to the final brief given to the multimedia designer. Understanding behavior associated with the intersection of the social interactions of students, the physical and digital tools, and the development of ideas as part of the design process is vital to the design of *learning by design* projects in the future.

Endnotes

(1) The Design Studio is a multimedia educational design research facility at the University of Sydney: http://sydney.edu.au/research/stl/facilities/EDRS/index.shtml

(2) Retrieved from: https://dschool.stanford.edu

References

Berger, J. (2007). *Berger on drawing* (2 ed.): Aghabullogue, Co. Cork : - Occasional Press.

Buxton, B. (2007). Sketching User Experiences: Getting the Design Right and the Right Design. Redmond, Washington: Microsoft Research.

Eppler, M. J. (2007). Toward a visual turn in collaboration analysis? *Building Research & Information*, 35(5), 584-587. doi: 10.1080/09613210701355724

Eppler, M., & Burkhard, R. (2006). *Knowledge Visualization Encyclopedia of Knowledge Management*: Idea Group Inc.

Ferguson, E. S. (1992). *Engineering and the mind's eye*. Cambridge, Mass: MIT Press.

Goldschmidt, G. (1991). The dialectics of sketching. *Creativity Research Journal*, 4(2), 123-143. doi: 10.1080/10400419109534381

Goodyear, P., Jones, C. & Thompson, K. (forthcoming) Computer-supported collaborative learning: Instructional approaches, group processes and educational designs. In Spector, M., Merrill, D., Elan, J., &Bishop, M. J. (Ed) *Handbook of Research on Educational Communications and Technology.*

Hansen, Y. M. (2000). Visualization for Thinking, Planning and Problem Solving. In R. E. Jacobson (Ed.), Information design (pp. 193-220): MIT Press.

Henderson, K. (1999). *On line and on paper: visual representations, visual culture, and computer graphics in design engineering.* Cambridge, Mass: MIT Press.

Hmelo, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to Learn about Complex Systems. *The Journal of the Learning Sciences, 9*(3), 247-298.

Hokanson, B. (2008). The Virtue of Paper: Drawing as a means to innovation in instructional design In L. Botturi & T. Stubbs (Eds.), *Handbook of Visual Languages for Instructional Design: Theories and Practice*s (pp. 76-89). New York Information Science Reference.

Kennedy-Clark, S. & Thompson, K. (accepted). Using multimodal discourse analysis to identify patterns of problem solving processes in a computer-supported collaborative environment. In Sudweeks, F. & Lim, H. (Eds) *Innovative Methods and Technologies for Electronic Discourse Analysis.*

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., Puntambekar, S., et al. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design into practice. *The Journal of the Learning Sciences*, *12*(4), 495–547.

McGown, A., Green, G., & Rodgers, P. A. (1998). Visible ideas: information patterns of conceptual sketch activity. Design Studies, 19(4), 431-453. doi: 10.1016/s0142-694x(98)00013-1

Suwa, M., Gero, J., & Purcell, T. (2000). Unexpected discoveries and S-invention of design requirements: important vehicles for a design process. *Design Studies*, 21(6), 539-567. doi: 10.1016/s0142-694x(99)00034-4

Suwa, M., & Tversky, B. (2002). External Representations Contribute to the Dynamic Construction of Ideas. Paper presented at the Proceedings of the Second International Conference on Diagrammatic Representation and Inference.

Thompson, K., Ashe, D., Carvalho, L., Goodyear, P., Kelly, N., & Parisio, M. L. (accepted). Processing and visualizing data in complex learning environments. *American Behavioral Scientist.*

Thompson, K., Ashe, D., Yeoman, P., & Parisio, M. (accepted). Phases of design: Following idea development and patterns of collaborative discussion in a *learning by design* project. *The 10th Int'l Conference on Computer Supported Collaborative Learning,* Madison, Wisconsin.

Thompson, K., & Kelly, N. (2012a). Combining collaboration spaces: identifying patterns of tool use for decision-making in a networked learning environment. Paper presented at the *Eighth International Conference on Networked Learning*.

Thompson, K., & Kelly, N. (2012b). Processes of decision-making with adaptive combinations of wiki and chat tools. Paper presented at *The Future of Learning: Proceedings of the 10th International Conference of the Learning Sciences (ICLS 2012*).

Vattam, S. S., & Kolodner, J. L. (2008). On foundations of technological support for addressing challenges facing design-based science learning. *Pragmatics & Cognition*, *16*(2), 406–437.

Zenios, M., & Holmes, B. (2010). Knowledge creation in networked learning: combined tools and affordances. Paper presented at *the 7th International Conference on Networked Learning 2010*.

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