New Review of Hypermedia and Multimedia,
Vol. 13, No. 2, December 2007, 135–162

Representing Collections as Compositions to support distributed creative cognition and situated creative learning

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We investigate how the creativity support tool combinFormation supports the creativity-oriented course, The Design Process, by representing collections as compositions. Undergraduate students in The Design Process are charged with working in interdisciplinary teams to develop new inventions. combinFormation is a mixed-initiative system that integrates browsing, searching, representing, manipulating, and collecting digital information resources, using the form of the visual composition space. Students use the composition space to develop collections of prior work that support their creative processes of developing new inventions. A quantitative study shows the overall effect of mixed-initiative composition on the performance of student groups on creative projects. To understand the mechanisms of situated creativity support, we follow-up with case-study interviews of two project teams. We develop the frameworks of distributed creative cognition and situated creative learning to analyse the interview data. We find that the mixed-initiative capabilities of procedural generation and human manipulability of visual information representations in the composition space support distributed creative cognition and situated creative learning.

1. Introduction

Since innovation is so economically (Bollier 2000) and psychologically (Csikszentmihalyi 1991) significant, it is imperative for us to cultivate innovation practice in education. We need to discover new forms for curricula that engage students in creative invention processes, and for creativity support tools that catalyse the fuel of growing digital repositories to power creative efforts. Creativity-oriented courses require students to produce new knowledge, instead of simply reproducing existing knowledge. *The Design Process* is an undergraduate course assembled with the overall goal of engaging interdisciplinary students in creating new inventions. The students often work collaboratively, in teams. As in most processes of research, the prior work collection plays an important role in processes of developing and validating new ideas.

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New Review of Hypermedia and Multimedia
ISSN 1361-4568 print/ISSN 1740-7842 online
http://www.tandf.co.uk/journals
DOI: 10.1080/13614560701711859

Hutchins articulates the importance of representations in team performance of information processing tasks while analysing communication among team members (1995). He distils an emphasis on how, "The technology in use externalizes certain cognitive processes... with some kinds of media supporting externalization of function better than others." The present research is oriented generally to developing better representations for functions of creative cognition, and specifically to investigating how these representations, when applied to collecting prior work in the situated context of The Design Process course, support teams of students performance on invention projects. combinFormation is a creativity support tool, which procedurally generates representations of collections of digital information in the form of visual composition, while also enabling the human participant to manipulate the collection-as-composition form. The goal of this paper is to tell stories in which visual composition representations externalize relationships among component contributions to an invention, affecting individuals' processes of creative ideation, and communication among team members.

According to Lave and Wenger (1991), learning is a situated practice in which cognition and social interaction are connected. Hollan and Hutchins (2000) see cognition as distributed across groups of collaborating individuals and the artefacts that they employ, which represent aspects of the processes of their collaboration. Creative cognition psychologists identify specific cognitive processes and structures that contribute to creative processes and products (Finke *et al.* 1992). These include *ideation*, the development of new ideas, *incubation*, time spent away from a creative task, and *provocative stimuli*, unexpected representations that excite subjects to ideate. We connect distributed cognition, situated learning, and creative cognition to develop a framework of *distributed creative cognition* and *situated creative learning* to analyse case-study data that investigate how combinFormation's visual information representations, procedural generation of digital information collections as compositions, and support for human manipulability contribute to creativity and learning.

This paper begins by introducing the situated context of The Design Process course, and the role of digital prior work collections in collaborative creative student projects. The next section takes a metadisciplinary approach (Kerne 2002) to developing the representations of combinFormation's mixed-initiative composition space, addressing components such as visual cognition, composition as form, procedural generation of information, and manipulability. The subsequent section develops this paper's major analytic frameworks, *distributed creative cognition* and *situated creative learning*, through the basis of their constituents in prior research. This sets the stage for introduction of our study design, and the presentation of quantitative and qualitative data. In the qualitative data presentation, we see how the visual representations of the collection-as-composition, procedural generation of diverse information that function as provocative stimuli, and human manipulability of compositional design support distributed creative cognition and situated creative learning.

2. Situated context: Collaborative creative projects in *The Design Process* course

The Design Process is an innovative interdisciplinary undergraduate course on creativity, innovation, and entrepreneurship. The course engages students in design thinking, problem-based learning, idea generation, knowledge creation, and future studies. The course has been developed by Eppright Professor of Teaching Excellence Rodney Hill. Students are charged with creating new knowledge, rather than just replicating existing knowledge. They develop new inventions. Each participant must complete a non-disclosure agreement at the semester's start. Some will register the intention to file patent applications from class projects. The structure is designed to promote student initiatives in education, through participatory processes that are open-ended, social, and constructive.

Approximately 330 students per semester participate in The Design Process course each semester, with substantial representation from science, engineering, business, liberal arts, and architecture. For most assignments, the students work collaboratively in heterogeneous gender-balanced and interdisciplinary groups of six (Kerne *et al.* 2006). In this paper, we present data gathered during the fall semesters of 2005 and 2006. Two class projects, The Hybrid and The Invention, were of particular importance during these periods.

For *The Hybrid*, students were asked to "create the future by combining and connecting any services or objects that have never been linked before and illustrate a new service or idea." They were asked to search the Internet and the Patent and Trademark Library to find and collect the most relevant prior work. This *prior work collection* forms a basis for assessing novelty, and functions as a means for developing source materials in the form of existing services and objects that are combined. Creative products were presented to the class. The presentation, and its materials (typically PowerPoint slides) were evaluated. A subsequent assignment, *The Invention*, required the student project teams to "create original inventions from your creative depths, journals or a posted Bug List." Like The Hybrid, The Invention requires students to assemble and present a collection of prior work, and make a presentation of creative products. The present research addresses and supports the prior work collection requirement for students of The Design Process working on these assignments.

The prior work collection is a personal collection of digital information resources. Its development is essential to many modes of scholarship and research, including reports, theses, publications (like this one), and marketing plans, as well as for the development of new inventions. Types of prior work include *needs*, which ground the significance of a new invention, *ingredients*, which serve as building blocks in the invention's construction, and *precedents*, which are the most similar previous undertakings. As members of the combinFormation research team, we have developed this articulation of what prior work is through collaboration with the professors and teaching assistants (TAs), of The Design Process course. Iterative refinements of curricular constituents are regularly fed back into the specification of the assignments and other aspects of the course design.

3. Composition: Manipulable visual information representations

Prior representations of digital collections, such as those assembled by search engines, through spatial hypertext (Marshall and Shipman 1994, Rosenberg 2001, Nakakoji *et al.* 2005), and by research publication authors (such as the references section of this paper), are textual in nature. Some of these are fixed, list forms. In some, the participant is responsible for the process of assemblage. In this section, we motivate the need for visual image and text representations, which emphasize the function of collections as artefacts that support communication, while mixing procedural generation of elements, and human manipulation of design and organization. This leads to the introduction of the combinFormation mixed-initiative system for developing personal information collections as compositions of image and text surrogates (Kerne *et al.* 2006).

3.1 Visual image and text representations promote cognition

Diverse studies have found that visual representations that connect images with text promote cognition. In the working memory system, the visuospatial buffer (which stores mental images) and the rehearsal loop used for words are complementary subsystems (Baddeley 1992). They support each other in combined image-text knowledge representations. Glenberg established that the combination of an image and descriptive text promotes the formation of mental models, and extends working memory capacity (Glenberg and Langston 1992, Glenberg 2002). Carney and Levin (2002) and Mayer and Moreno (2002) found that dual coding strategies enhance cognition during educational experiences of digital media. Text disambiguates images while engaging complementary cognitive subsystems. Thus, combining images and text while forming surrogates makes better use of cognitive resources than text alone, and improves navigation (Kerne *et al.* 2005). Marchionini *et al.* investigated the use of multimodal surrogates for video browsing (Ding *et al.* 1999, Wildemuth *et al.* 2003) by comparing users' performance and experience using different surrogate formats for digital videos. Combined surrogates lead to better comprehension and reduced human processing time. Woodruff *et al.* discovered the efficacy of "enhanced thumbnails", each annotated with text callouts of search queries (2002).

Our approach builds on these results. combinFormation forms image and text surrogates to represent documents and their constituent ideas by automatically extracting relevant clippings. A surrogate enables navigation back to the source document (Burke 1999). Clippings are extracted procedurally, by generative algorithms (Kerne *et al.* 2006). The participant may also extract relevant clippings manually, using click and drag to select in the standard Web browser, followed by drag and drop to the combin

Formation composition space. Clippings are important constituents of prior work collections, because they highlight elements from the source document that are of particular relevance to the invention task at hand. Representing surrogates with image and text clippings in combinFormation is designed to promote participants' quick understanding of the ideas inherent in information resources, enable navigation, and provide citation document metadata interactively as *in-context details on demand* (figure 1).

3.2 Representing collections as manipulable compositions

The list of textual surrogates is typically used to represent collections, such as search result sets and bookmarks. Composition is an alternative to lists; literally, it means, "the act of putting together or combining... as parts or elements of a whole" (Oxford English Dictionary 1992). Composition of image and text surrogates extends the organizing of information afforded by spatial hypertext (Marshall and Shipman 1994, Rosenberg 2001, Nakakoji *et al.* 2005) by emphasizing visual design and communication. Spatial hypertext allows a participant to incrementally instantiate, organize, and structure elements and their relationships. Composition uses visual design techniques that connect and layer elements (Tufte 1990) to form a coherent whole. Visual techniques include image representations, text stroking, and compositing, as well as relative size relationships, colours, and typefaces. Connecting elements visually is important because it promotes chunking, a means for overcoming the 7 ± 2 entities capacity limitation of working memory (Miller 1956, Simon 1975). This research addresses the processes through which collections are assembled, and how the resulting forms function as artefacts for communication and navigation, and stimuli for cognition. By composition space, we mean the interactive environment in which the process of putting the composition together occurs.

3.3 combinFormation

combinFormation is a mixed-initiative system for developing personal collections of information resources through composition of image and text surrogates (Kerne *et al.* 2005, 2006, Interface Ecology Lab 2007). The goals of the system are to make the ideas found in information resources visible, and to give participants the opportunity to see and manipulate relationships among them. This, in turn, can stimulate the essential step of cognitive restructuring that can form a basis for creative ideation. Rather than attempt to make the machine think independently, this creativity support tool, in the new tradition of mixed-initiatives (Horvitz 1999), uses a model of aggregated information and media semantics to gather and represent information to stimulate the participant's cognitive processes. Thus, as in a typical search engine interface, results are gathered automatically in response to a search query. However, this procedural generation places visual representations into the composition space, where the participant can manipulate them. The

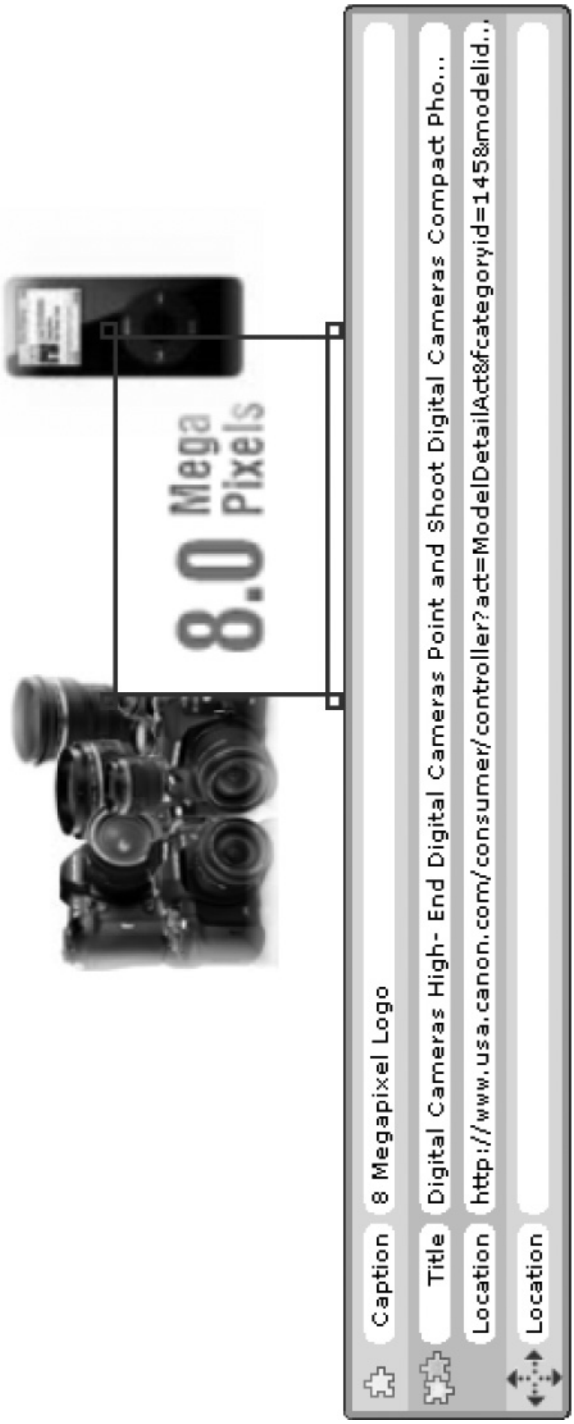


Figure 1. Surrogate with in-context metadata details on demand.

human, as a source of feedback and direction, plays a key role in the operational loop (figure 2). Each surrogate serves as an interactive affordance (Norman 1988) for thinking about significant ideas, for expressing interest that directs the agents, and for navigation.

Figure 2 provides an overview of the mixed-initiatives that the participant and agent can engage in, through the composition space. It shows their relationships, how they affect each other, the composition, and the model of information and media semantics and participant interests. Through seeding, the participant points the agent at particular information sources, for example by specifying one or more search queries. The combinFormation interface enables participants to input multiple queries and select a specific search provider for each, including Google, Yahoo, Yahoo Image Search, Yahoo News Search, Flickr, or Delicious. The agent uses the seeding specifications as the initial basis for generative information collection and temporal visual composition. It processes search results, extracting image and text clippings that function as surrogates.

The composition and its surrogate components serve as a visible medium for communication between human and agent, and between human and human, as the visual record of a process of collecting, sharing, and thinking about information resources. The model of aggregated information and media semantics and the participant's interests serve a similar intermediary function, but in a purely computational form. The agent engages in processes of finding, forming, and presenting relevant information based on the semantic model, which represents the participant's initial seeds, all resulting documents that are encountered, the structure of the found information, and subsequent interest expressions. The participant can navigate from any surrogate to its source document. The participant can turn the agent initiatives off and on, and also provide relevance feedback through interest expression that affects the model. The media semantics and participant

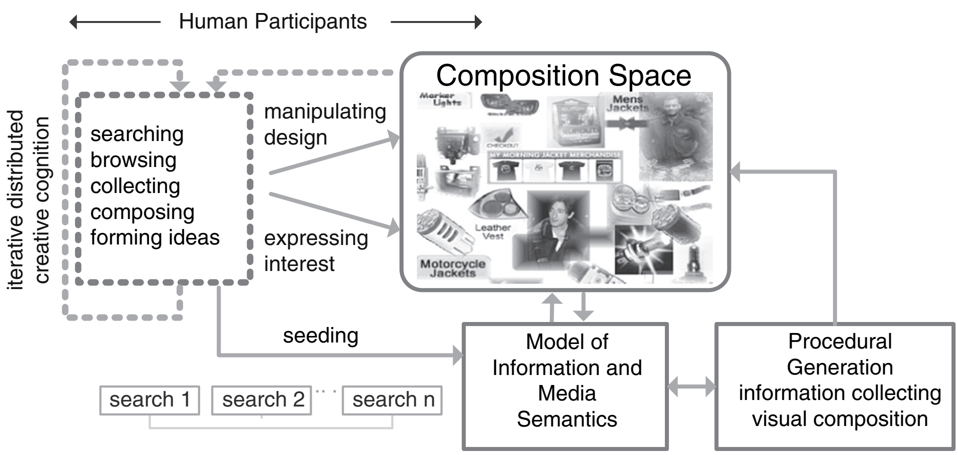


Figure 2. Situated interactions of human beings and digital representations in the mixed initiatives of the visual composition space: procedural generation and human manipulation.

interests model, in turn, serves as the basis for the agent's initiatives of collecting information and generating temporal visual composition.

Participants manipulate the visual and semiotic design of the collection in the composition space. They can cut, resize, and rearrange surrogates in the space. They can also drag and drop interesting elements from the Web browser into the space, and create their own text elements by creating a text box using a text tool. Participants can create a hyperlink to an element by drag and drop of a URL onto the element. Using the text tool, they can also edit text in existing surrogates. Affordances for changing design are provided in context, next to a surrogate, when the participant brushes it with mouseover. For each text surrogate, the participant can change stroke colour, font style, and font size. For image surrogates, the participant can change the border transparency to form alpha gradients, which create the effect of *compositing* adjacent elements. Compositing creates visual blends, contrasting with the cut-and-paste adjacency juxtaposition style of hard edges and clear lines, which is better for representing relationships among elements while maintaining more individual characteristics.

Participants preserve their collected compositions by selecting save in a menu. In response, combinFormation stores XML, JPG, and HTML files. Participants can reopen what they saved in combinFormation with the XML file. They can publish or e-mail their HTML and JPG files to most easily share their collections.

4. Situated creative learning and distributed creative cognition

We integrate situated learning, distributed cognition, and creative cognition to develop a framework of analysis, which will be used to interpret the data. Situated creative learning and distributed creative cognition are new terms, which we derive through this integration of significant prior methodologies.

4.1 Situated learning

Situated learning is an approach that connects the roles of social practice and cognition in learning experiences (Lave and Wenger 1991). Each instance of learning is situated, an integral part of a generative context of social practice. This emphasizes the interdependency of students, teachers, the world, activities, meaning, cognition, learning, and knowing. Learning is constituted as participation in a community of practice in the social world, in which an evolving set of relationships is continuously renewed. Meaning is negotiated among participants. Knowledge is socially mediated and open-ended. "As an aspect of social practice, learning involves the whole person; it implies not only a relation to specific activities, but a relation to social communities... Activities, tasks, functions, and understandings do not exist in isolation; they are part of broader systems of relations in which they have meaning." The student project teams in The Design Process function as communities of practice, in which situated learning develops. The students are assigned to the groups by course teaching assistants, so, in most cases, they do not begin as friends. Over time, it seems that successful project teams implicitly develop an informal fabric of social relations, including mutual awareness and support, which contributes to their creative practice of invention development.

4.2 Active learning

Active learning is an approach from education that also emphasizes participation. Active learning refers to techniques in which students do more than simply ingest information. Students are engaged in activities such as discovering, processing, and applying information (Bonwell and Eison 1991). Students who actively engage with the material have been found to be more likely to recall information later and be able to use that information in different contexts (Bruner 1961). Active learning puts the responsibility of organizing what is to be learned in the hands of the learners themselves, and ideally lends itself to a more diverse range of learning styles. combinFormation is designed to provide an active learning space for learners to reconstruct, organize, and represent the found information on their own so that they can apply the information in new contexts and develop creative ideas.

4.3 Distributed cognition

Distributed cognition is a theoretical and methodological framework that constitutes cognitive processes beyond a single brain and body by using the functional relationships of elements that participate in the processes as the basis (Hollan *et al*. 2000). Cognition is embodied and situated through socially organized work activities. "In distributed cognition, one expects to find a system that can dynamically configure itself to bring subsystems into coordination to accomplish various functions." These functions span significant tasks and activities. Within this framework, cognitive activities are viewed as computations that take place via the "... propagation of representational state across media..." (Hutchins 1995, as cited in Rodgers 2004). The media here refer to human internal representations (e.g. individual human memories, with their associational structures) and external representations in the world (e.g. physical artefacts, such as paper, and computational artefacts, such as displays). We add that internal computational representations, such as combinFormation's model of aggregated information and media semantics and participants' interests, also function as a medium through which states are propagated. States of representation support the diverse ways in which information and knowledge resources are transformed during work activities, including transfer from human to human, from human to computer, from computer to human, and from computer to computer. To analyse how a given activity is conducted and coordinated, attention is focused on the interactions that take place across representational media through situated actions. Mechanisms for propagating knowledge across representational states include verbal dialogue, non-verbal communication, the transformation of information between different modalities (e.g. verbal message to a keyed input), and the construction of new representations. In the present research, we pay particular attention to how the visual information representations of combinFormation composition spaces function as: (1) a means of communication to a human participant from digital repositories and search engines, (2) cognitive stimuli that serve to help humans think about relationships between ideas and components, and (3) communicative artefacts that represent processes of invention development among collaborating project team members.

4.4 Creative cognition and information discovery

Distributed cognition's basis in practice contrasts with creative cognition's tradition of experimental empiricism. The creative cognition approach views creativity as the product of many types of mental processes, each of which helps to set the stage for creative insight and discovery (Finke *et al*. 1992). These include mental models, mental blends, and combinations. Preinventive properties that support creative search and exploration include novelty, ambiguity, and incongruity, because these properties can form the basis for flexible representations that contribute to cognitive restructuring. Restructuring often serves as a precursor to the emergence of new ideas, also known as *creative ideation*. *Incubation*, in which a rest is taken from direct work on a creative task, and *provocative stimuli*, unexpected information representations that may somehow be connected to the task at hand, though not in an obvious linear way, have been shown to promote ideation (Smith 1994, Shah *et al.* 2003).

In many cases, interactive systems are evaluated with tasks that have a single correct answer (e.g. Woodruff *et al.* 2002, Wildemuth *et al.* 2003). Creative cognition practitioners call these *convergent thinking* tasks (Finke *et al.* 1992). Latency, the time to completion, and accuracy, the correctness of answers, are typically employed as metrics. In contrast, *divergent thinking* tasks are open-ended questions that have many possible answers. Divergent thinking tasks conducted in the context of information finding and organizing, are known as information-discovery tasks (Kerne and Smith 2004). In *information discovery*, the participant's task is to develop new ideas (creative ideation) while finding and assembling relevant information. Found information may function as provocative stimuli that promote ideation. Information exploration can lead to the refinement of a vague information need that leads, through interaction with information resources, to a more thorough sense of the problem at hand. combinFormation supports information discovery and exploration by providing support for evolving information needs, utilizing visual representations, generating unexpected results and combinations, and providing flexible and manipulable representations of collections.

4.5 Distributed creative cognition and situated creative learning

Through the term *distributed creative cognition*, we mean to address creative ideation processes that occur in distributed environments of participants, artefacts, context, and practice. When cognition is distributed across multiple participants, we need to understand how artefacts and processes contribute to creative ideation. A key focus will be on the role of digital representations, such as the composition space, in promoting the emergence of new ideas.

Similarly, with the formulation *situated creative learning*, we address learning processes in which the goals go beyond pre-defined learning skills and methods, to developing new creative forms and products. What role do representations play in situated social interaction? How are participants stimulated by ambiguous and fully finished representations, in different stages of the creative process? How does an interactive system such as combinFormation support this? How do the mixed-initiative roles of software agents and manipulability of the representations affect collaborative student project groups in situated practices of learning and invention?

5. Study design

We designed and conducted a comparative field study in The Design Process course. This is challenging, because unlike in a laboratory, where the experimenters can manipulate conditions, the course conditions must be fair to all students. They also must meet the course's educational needs and negotiate established practices. We arranged an appropriate form of situated study. Students used either combinFormation or Google and Word to collect prior works for their Hybrid and Invention projects. Half the class was assigned to use the mixed-initiative composition system, combinFormation, for the prior work collection on The Hybrid, with the other half of the class using Google to search and Word to assemble relevant results (Google + Word). For The Invention, the groups switched. Thus, each half of the class used combinFormation for one assignment, and Google + Word for the other. This was fair to students, while providing comparative conditions for study.

Each of the course's two sections has a Teaching Assistant. This TA assigns grades for all of the assignments performed by students in that section. The TA evaluated both components of the assignment—the prior work and the creative products—for both projects. The criteria and process for evaluating the creative products were established in The Design Process in prior years, before combinFormation's introduction there. For the creative invention products, the criteria involve originality, novelty, practicality, broad impact, and commercial transfer potential. We did not change this. For the prior work, The Design Process course and combinFormation research teams collaborated to establish criteria for evaluation: how informative, communicative, and expressive, the collection is, and the extent of variety among the collected resources. For both components of both assignments, a new

1–5 scale was instituted for the study. This scale corresponds directly to the letter grades that are assigned in the course.

To further understand the experiment design, it is important to note that the relationship between The Design Process (TDP) course team of professors and teaching assistants, and the combinFormation research team is one in which independent entities cooperate. Our sources of funding are entirely separate. While our goals overlap, they are established independently. TDP team's goals are based in creating an environment in which students learn to be creative; the combinFormation research team's goals are based in developing digital tools that promote creative experiences.

We continued the practice of having each course TA evaluate all assignments performed by students in his section. We discussed trying to mix up the grading, so that one TA would grade the prior work, and another would grade the creative products. This seemed to make sense from the standpoint of experimental validity, because it increases the independence of the evaluations. However, it does not make sense in the context of the course. Here, the TA assigned to a particular section gets to know many of the students. This knowledge becomes part of how assignments are graded in any course. It is a situated social practice. It does not make sense to separate evaluation of assignments from these grounded moorings. The course's TAs are responsible to the course, and its educational goals, and not to the combinFormation project, and its research goals. They have no stake in the success of our research, and a high level of accountability to their students. They are expert evaluators. Thus, this methodology is the only practical and most valid one for this research. Any process of evaluation by others would be more artificial and less grounded in truth.

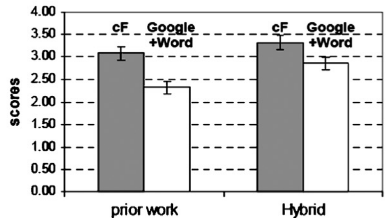
We present two kinds of data. The first are the result of a quantitative study, conducted in fall 2005, which examines the performance of student groups on the creative projects. The independent variable was the tool used for collecting prior work, either combinFormation or Google+Word. Subsequently, we present a qualitative study, conducted in Fall 2006, which examines situated creative learning practices using combinFormation, through case-study interviews.

6. Quantitative data

In fall 2005, we performed a study involving 182 students who were enrolled in one section of The Design Process. Approximately 81% of the students performed The Hybrid assignment: 32.4% used combinFormation to develop the prior work collection; and 48.4% used Google+Word. Those who used combinFormation scored an average of 3.08 on the prior work, compared with 2.32 for those who used Google+Word, and the difference was significant [$t(118) = 3.528$, $p = 0.001$]. Even more importantly, those who used combinFormation also scored higher (3.32 vs. 2.85) on the creative products for The Hybrid assignment, and again, the result was statistically significant [$t(145) = 2.227$, $p = 0.028$] (figure 3 left).

	cF	Google +Word	not involved	total / average
# of students	59	88	35	182
% of students	32.4%	48.4%	19.2%	100%
prior work	3.08	2.32		2.63
Hybrid	3.32	2.85		3.04

	cF	Google +Word	not involved	total / average
# of students	61	98	23	182
% of students	33.5%	53.9%	12.6%	100%
prior work	3.13	2.38		2.66
Invention	3.41	2.85		3.06



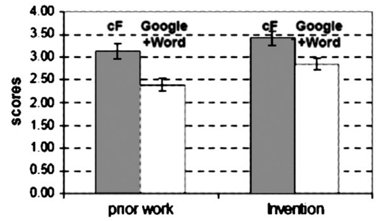


Figure 3. Left: Student scores on the Hybrid assignment; Right: Student scores on the Invention assignment.

The findings were similar for The Invention assignment. This time, 33.5% of the students used combinFormation, out of a total of 87% who did the assignment (figure 3 right). None of these were students who used combinFormation on The Hybrid; 53.9% used Google + Word for creating their prior work collection. The scores for the prior work collection were 3.13 for the combinFormation users vs. 2.38 for Google + Word [$t(141) = 3.843$, $p < 0.001$]. For the creative products of The Invention, the scores were 2.85 vs. 2.38 [$t(157) = 2.716$, $p = 0.007$]. The score differences for the prior work and for the creative products on both The Hybrid and The Invention were statistically significant, indicating that using combinFormation improved creativity for the class as a whole. The students created better invention products when they used combinFormation to develop the prior work.

7. Qualitative data: Case studies

In fall 2006, we investigated the impact of representing collections as compositions in The Design Process course. There were 328 students in the two sections of the class. The quantitative study established that combinFormation improved creative invention, but did nothing to identify the contributions of particular components. So, here, we studied the best cases in order to understand how representing prior work collections with mixed-initiative composition spaces contributes to distributed creative cognition and situated creative learning in information discovery scenarios of invention and research. A goal was to provide a basis for deciding which capabilities should be amplified in future research and development. Two exemplary project teams were selected, based on their excellent Hybrid project scores, and asked, through an e-mail sent only to members, to participate in a group interview about how they developed their invention projects. In addition to having used combinFormation on The Hybrid, the project teams also possessed ample experience using Google and Word, and so were able to provide comparative perspectives on how their experiences collecting prior work for The Hybrid project differed from other experiences searching and collecting. Demographic information describing the interdisciplinary, gender-balanced membership of each of the two featured groups is presented in table 1. The members of each group met in person with the interviewer and talked informally, in a semi-structured interview about their group's invention development process, including use of combinFormation. Each group interview took around an hour. Due to the open-ended nature of the assignment, each group's invention was distinct. The Hybrid project of Group 1 was called *Blinker Jacket*, while that of Group 2 was *iPod+Camera*.

Our analysis and presentation of qualitative interview data are based on these codes, which are connected to components of creative cognition:

1. the topics of the inventions and the processes through which project teams developed deliverables;
2. the role of visual representations;
3. the procedural generation of provocative stimuli;
4. human manipulability of information in the composition space; and
5. the overall role of combinFormation's mixed-initiative composition space in distributed creative cognition.

Students in the interviews said that combinFormation supported them in developing and refining creative ideas for their projects. The coded data show how combinFormation's mixed-initiative composition space supports distributed creative cognition and situated creative learning in situated practices of The Design Process assignments.

Table 1. Demographic information: members of Group 1 and Group 2 involved in the interviews.

Group 1		
M1	Senior	Finance Major
M2	Junior	Biomedical Science
M3	Sophomore	Landscape Architecture
F1	Junior	Business Major
F2	Junior	Agriculture Business
F3	Sophomore	Business Major
Group 2		
M4	Junior	Finance Major
M5	Senior	Civil Engineering
M6	Junior	Philosophy
F4	Senior	Animal Science
F5	Junior	Kinesiology
F6	Junior	Business Major

7.1 Topics of inventions and processes of collaborative development

Group 1's Hybrid project was called, "Blinker Jacket." Group 2's project was iPod + Camera. We examine data about how each group collaborated to create their Hybrid.

7.1.1 Group 1 invention: *Blinker Jacket*. Group 1 developed their Hybrid idea from an awareness of the problem of bicycle fatalities that occur at night. They were motivated by the following statements by Riley Geary, an analyst of US Bicycle Traffic Fatalities.

> Adult urban cyclists now constitute the dominant modality among bicycle traffic fatalities in general. Night-time fatalities comprise at least half the problem in this class. This is out of all proportion to the amount of urban cycling actually being done at night, and strongly suggests more attention needs to be given to the entire night-time bicycle conspicuity problem.

To make it safer for both bicyclists and motorists at night, they developed the Blinker Jacket (see illustration, figure 4). The Blinker Jacket is a jacket that has blinking sleeves. When you need to make a right turn, the entire right sleeve becomes activated in a blinking state, like a turn signal on a car. This makes it easier for car drivers and motorists to see the position and trajectory of the bicyclist.

Group 1 students met together and brainstormed about their group project ideas. Several project ideas were brought up during their initial group meeting. They agreed to develop the Blinker Jacket for their project. Group

Figure 4. Blinker Jacket hybrid: Lights blink on the side of the arm of which direction you wish to turn.

members divided the work into parts; each student performed their part of the work individually. The group member who originally raised the idea of the Blinker Jacket, F2, was in charge of developing the product prototype. M2 and F1 collected prior work using combinFormation (figure 5). F3 combined all individual works and made the PowerPoint slides with M1 for the presentation. M3 and F2 were responsible for developing a skit for the presentation.

While they worked individually, Group 1 members needed to communicate with each other to coordinate their activities. They used e-mail to engage in dialogue about project issues and share their evolving results. Continuous

Figure 5. Prior work collection for Group 1's hybrid project, *Blinker Jacket*, developed as a composition, using combinFormation.

communication through digital media supported their collaboration. In order to develop and share ideas and address issues, they utilized visual representations of their research-in progress, such as the combinFormation composition and diagrams, in tandem with text descriptions. As each participant finished their part of the assignment, they integrated them into the final group project. Visual representations functioned as essential media of distributed creative cognition:

> M1: I found that when we try to work in a group for a single thing it slows down. I think that the best way to do a group project is that everybody does all their portions of the project individually and then we meet again to combine those. A group working together in a single task seems inefficient. It is usually like one person sitting in front of a computer and others are around watching. Instead, we worked individually on assigned parts, and kept communicating with each other digitally.

Collaboration requires shared understanding (Stahl 2005). Digital representations support communication, which serves to coordinate and advance development. The students who finished successful invention projects as a group said that they keep communicating each other using digital media such as e-mail while they were not collocated.

7.1.2 Group 2 invention: *iPod+Camera*. The Hybrid idea of Group 2 was to combine an iPod with a camera. (Note: This project was developed approximately 4 months before Apple's iPhone announcement.) They sent each other e-mails about several project ideas, and decided *iPod+Camera* would be the best idea to develop for their project (see illustration, figure 6). Then, they met together and used combinFormation to collect prior work and discuss their project (figure 7). While they were searching for and browsing information with combinFormation, they were able to discuss found information and develop a detailed design specification for their final project. Visual representations of information supported their group communication; procedurally generated information was utilized in a collaborative process of think-aloud. The representations helped them coordinate their actions.

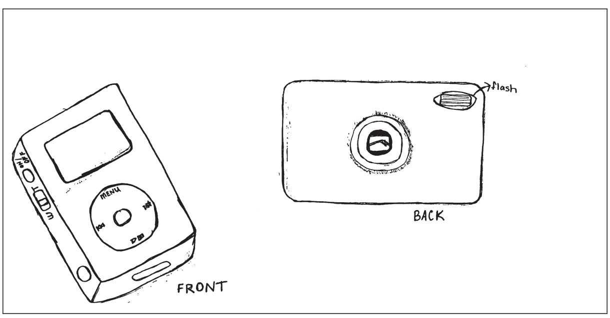


Figure 6. Sketch of Group 2's project, *iPod+Camera*.

Figure 7. Prior work collection for Group 2's project, *iPod+Camera*, developed as a composition, using combinFormation.

M5: For the most part, the concepts and workings in combinFormation were good. We came up with the idea on our own, and then met together and put all relevant information together. We were all sitting together to collect the prior work using combinFormation.

F5: We met in the F4's office. She sat in front of a computer monitor and controlled a mouse to make the combinFormation composition. Others were standing around her and saying 'get that', 'get that'. We talked and discussed about found information elements and our project idea while using combinFormation.

Group 2 created a collection of prior work using combinFormation through face-to-face collaboration. This process stimulated them to engage in distributed creative cognition. Dialogue about found information stimulated the emergence of new design possibilities for their group project.

7.2 Visual representations for distributed creative cognition

The visual representation of information supported students in understanding information effectively, and in promoting clear communication among group members. Students said that they liked to have both images and text better than to only have text information because it is easier to understand and explain to others. The image and text representations facilitate the situated negotiation and renegotiation of meaning in the world, which is an essential aspect of participation in situated learning.

combinFormation is good for expressing ideas to others. Visual compositions are appealing; they catch people's attention. One student said that when looking at the composition his collaborator created, he was inspired. With combinFormation, students said they were able to show connections between different information elements without wordy expression. The members in Group 2 said that they found combinFormation useful and efficient for preparing their class presentation. They did not need to pull out information from somewhere else, and then take the additional step of pulling it into PowerPoint, because combinFormation integrated finding, collecting, and representing information. Instead of PowerPoint, they utilized a composition as the basis for their final presentation, to present their project ideas to the class.

F6: "I like the visual appearance of information and different ways of looking at information in combinFormation. combinFormation brings a lot of information. In class, we had so many PowerPoint presentations. We don't have to drag image and text information from other sources, and format it. combinFormation just gives you information which is from sifting through all different resources. It was much easier to prepare presentation materials."

F4: "You do not need to worry about how to prepare a visual form to present, because combinFormation just did it for you. It just makes it easy to combine separate processes (finding information and visually presenting information) into one."

> F4: "It is eye appealing. People will rather look at it rather than go through PowerPoint. The connections were right there in front of you. It was not wordy expression."

7.3 Provocative stimuli: Procedural generation of diverse information

The procedurally generated diverse visual representations of information by combinFormation functions as provocative stimuli. They help students to broaden the range of their invention ideas. Student projects tend to be similar because many students live in the same environment. Most of The Design Process students live in dormitory rooms on campus. In practice, many invention ideas turn out to be based on changing things in this environment. Through using combinFormation, students were stimulated to think more broadly about the world, because they saw visual information from the different spaces and different contexts.

> F3: Students' projects were similar because the ideas were coming from the same place and the same environment, which they are looking at and living in every day. However, using combinFormation you can overcome the limitations by seeing images with the different aspects and environments.

> M1: Right, the room (Dormitory room) was a kind of end of students' invention.

> M2: Changing things around the campus was also the most popular invention topic.

Both Group 1 and Group 2 launched combinFormation with multiple search queries. Group 1 searched for 'car light' and 'jacket' using combinFormation. They mixed together many kinds of lights and jackets. They saw many formations of how those lights and jackets can be combined together. They liked the way the combinFormation brings diverse search results into one space. Using Google and a typical Web browser, they could see only one information resource at a time.

Group 2 searched for 'iPod' and 'camera'. In Group 2's experience, combinFormation brought everything they wanted to look at from multiple searches into the composition space. Also, Group 2 used combinFormation's interest expression mechanism, because at first they got many iPod images compared with camera images. They expressed negative interest in iPod images. Then, they started to see fewer iPod images and more camera images. This helped them collect balanced information contributions from iPod and camera.

The diversity of informative images and text clippings generated in the composition space helped students to think about different possibilities, developing relationships and forming ideas, in comparison with regular Google search. Through looking at the generated information, thinking, comparing, and combining, students could create and develop new ideas.

> M6: "You can use it to create a new idea and search a lot more different things than using Google search."

> M5: "Looking at combinFormation generating information, comparing and combining found information brings a new idea."

People often encounter unexpected information with combinFormation because the system retrieves many search result documents and then follows relevant links, while presenting information clippings from these varied sources. The unexpected information promotes creative thinking. The directedness of the Google interface affords more direct finding of expected information, but at the cost of being less likely to stimulate consideration of unexpected possibilities. Procedural generation of visual information representations functioned as a more stimulating medium of representation for distributed creative cognition.

> M2: They have a completely different look and feel. combinFormation brings up search results for you as opposed to Google. Google gives thousands of results that sometimes overwhelm you or are similar to each other. combinFormation throws you different information over time and you don't know what you are going to get from it even though you typed in your own search queries. combinFormation is more unexpected. Unexpected information that the system brought into the space promoted developing ideas.

For example, while Group 2 was searching, browsing, and collecting information about 'iPod' and 'camera', combinFormation generated a clipping that said, "8.0 megapixels". This provoked the group members to think more about details to specify for the camera in their invention prototype, which they otherwise would not have thought of.

> F6: An 8 megapixel image came up during the combinFormation search (figure 7, centre). It made us think about more specific details of our project's characteristics that need to be worked out.

As combinFormation keeps generating information, students said that they could learn about the topics by just watching the ongoing generation of the composition. They could compare information from different resources. Repetitive visual information from the same topic helped them discover trends and main areas.

> F3 [addressing use of combinFormation on another project]: I was mostly learning about what I am searching for using combinFormation... When I was searching for men's statues, I found many different head statues. For women, it came out more of whole body statues. It was comparing and learning differences between statues of men and those of the women. When I see repetitive things from same topic and contrast two different searches, I found myself discovering something that I have not known of.

Another student mentioned that his experience using combinFormation enabled learning about the search topics unconsciously, like learning a language by being with other people.

> F3: combinFormation is a better tool for learning rather than sitting down and reading a book. Watching random information seems like a learning a language by just being around people. You speak it without really trying to learn it.

combinFormation generates information clippings from documents, so students said that it brought more information a lot faster than Google and Word. They said relevant information was right in front of them to use, without the burden of clicking link after link. They found combinFormation fun and enjoyable because information was popping up like a video game.

> F1: I think combinFormation is more fun to use than Google. I do not like to go to Google and click on different result links and read to find what I need.

> M1: We need to go to all the Web pages and go through all the links using Google. In combinFormation, you can see the agent generating information and ideas for you. Google does not give any space of connections that might exist.

7.4 Human manipulability of information in the messy composition space

Students said that the composition space of combinFormation helped them see multiple connections between ideas extracted from diverse information resources. They said that that linear layout was hard to use to relate different ideas. However, using combinFormation, the students could combine and relate different ideas visually. In their view, Google is more structured. combinFormation is customized for participant orientation; it gives feel and sense to the search topics.

> M5: We can see multiple connections of things from different information resources in a spatial format.

> M1: Linear stuffs are hard to use to relate different ideas. Using combinFormation, you can combine different ideas and relate them visually. I think the best way to use combinFormation is for brainstorming.

During processes of human manipulation, continuously changing and emerging representations "talk back" to participants, allowing them to engage in reflection (Nakakoji *et al.* 2005) on the meanings of elements and their relationships. As the objects are repositioned, participants read the spatial representation to develop new understanding.

Students experienced the generated compositions as messy. They wanted to see results in a more structured format. The process of manipulating the layout to give it structure stimulates cognitive restructuring. While manipulating elements in the composition space, students found themselves thinking, developing understanding of information, and building ideas. For example, Group 1 said that when they moved jacket and light pictures around, they could visualize what they could make with lights and jackets, and what kinds of physical appearance and graphical aspects could be produced for the Blinker Jacket. They realized that so many different lights and different jackets were out there, prompting them to consider different ways to put them together. They played around with visual information in the composition space and made up interesting combinations by seeing what came up. Through their embodied interactions with the generated visual information representations, they developed complex relationships with the ideas and each other. Situated creative learning was stimulated by the generation, the representations, and the interactions.

Students said that they enjoyed manipulating elements, organizing them, and developing artistic products. They used the procedurally generated visual information element representations as building blocks for creative products.

> M2: I like things to be organized. I am an organizing freak. I organized and manipulated information elements in combinFormation to understand information. I developed and accidentally created ideas while I was manipulating elements. Also, information elements with ideas were bouncing in combinFormation.

> F1: I like things in an order. Through the process of making messy things organized, I came up with new ideas. If everything is linear and in order, there is no need to think anything new.

> F1: I liked to put together information and make collages. I enjoy making things arty.

7.5 Role of combinFormation's mixed-initiative composition space in distributed creative cognition

Hutchins (1995) emphasizes the role played by "the choice of representation of the input and the output and the algorithm to be used to transform one into the other," in the collaborative information-processing tasks of distributed cognition. Creative cognition involves ideation. Distributed cognition addresses the role of representations and social processes in collaborative work. The data here address gestalt impact.

While working with combinFormation, many students said that they found themselves forming ideas. Group 2 found combinFormation useful in collaboratively brainstorming about their idea, and then for presenting their ideas to the class. Because combinFormation procedurally generates so many different elements of information, combinations, and blends, it provokes participants to continuously think about new ideas. When students collaborated to develop creative ideas, they sometimes engaged in dialogue that included responding to combinFormation's procedural generation of new information in the composition space, and to each other, in real time.

Group 1 used combinFormation to develop their final invention project from an idea they developed beforehand. One participant articulated an overall sense of how these components support creative ideation.

> M2: For me, I think of combinFormation as an idea refinement tool. I couldn't picture our group project, 'Blinker Jacket', quite clearly in the first place. During work with combinFormation, I got to have some clear ideas. To me, it was something to build out, an idea foundation.

combinFormation's composition space changes the representation of the prior work collection to a visual form that integrates images and text, improving utilization of limited human cognitive resources. Students need to use tools to search for and collect information, generate representations, and interact with them; however, using the tools consumes cognitive resources, which then becomes cognitive overhead. The more cognitive resources demanded by the tools, the fewer cognitive resources students can spend on their own creative thinking (Streitz *et al.* 1989). The composition space's mixed initiatives change the process, by integrating searching, browsing, and collecting. This eliminates the cognitive load associated with running multiple applications, and context-switching between them.

The integration of functionalities and fluidity of representation enable the composition space with procedural generation and human manipulability to play significant interconnected roles in situated creative learning and distributed creative cognition. One student summed up these perspectives.

> M4: combinFormation is interactive and more. You decide what you want to use it for.

8. Discussion and conclusion

It is worthwhile to compare the present research with Hutchins's (1995) groundbreaking account of ship navigation and analysis of distributed cognition. Hutchins observed the best crews of ocean-going vessels that he could find, and also drew from accounts of skilled Micronesian navigators. The Design Process course involves diverse undergraduates. While none are experts per se, in the present investigation we interviewed students who performed well, in order to develop an understanding of successful practices.

The navigation and pilotage of ships is highly complex, and subject to many variables, which arise spontaneously in situated practice. This results in a dramatic near-collision in Hutchins' account, as well as in calmer episodes. However, navigation is essentially based on the interpolation of bearings and waypoints, including landmarks, celestial positions, and radar. Even though the lines of navigation may be very difficult to identify, and the social practices may be complex, the study of pilotage involves the calculation of convergences in bearings and lines of sight.

The study of collaboration in creative invention is even trickier, because it is not based on convergences of lines. There is no linearity at all. And so as researchers, we must assemble a breadcrumb trail of components of distributed creative cognition. In developing this methodology, we invoke creative cognition's research emphasis on mechanisms of creativity. At the same time, in this methodology we shift from that field's focus on laboratory studies to incorporate the emphasis on social practice and other components of ethnography, which characterizes distributed cognition and situated learning. It should be noted that we are engaged in mixed-method research that combines situated field studies like those reported on here with laboratory studies (e.g. Kerne *et al.* 2007).

The present research combines quantitative and qualitative data to develop a hybrid portrait of the impact of representing prior work collections with composition on distributed creative cognition and situated creative learning in the practice of undergraduate students working collaboratively to develop new inventions. The findings of the quantitative study of 182 students provide a strong overall basis for asserting that using combinFormation's mixed-initiative visual composition space to develop prior work collection promotes creativity in the student groups. Yet this finding does not tell us *how* creativity is promoted. To focus in on the significant mechanisms, we used case-study interviews with a small number of participants to identify mechanisms of combinFormation's support of creativity for interdisciplinary students learning to engage in open-ended processes of invention and design. This study instantiates situated learning theory's prescription for the development of active learning curricula, by investigating the perspective of students in everyday practice.

The development and evaluation of creativity support tools are important challenges for research. We developed a new analytical framework to address active learning practices in which creativity plays a fundamental role in education. Situated learning and distributed cognition are different sides of the same theoretical coin. One identifies learning as social practice, of which cognition is a part. The other extends cognition to account for collaboration, systems, and artefacts. Creative cognition is an orthogonal perspective, which focuses enquiry into the mechanisms of creativity. The present research integrates these methodologies, forming distributed creative cognition and situated creative learning, in order to understand how visual representations of information collections, and the mixed-initiatives of procedural generation and human manipulability contribute to the situated creative invention practices of collaborating student project teams.

Visual representations and the mixed-initiatives of procedural information generation and manipulability by humans play fundamental roles in distributed creative cognition and situated creative learning. Perceptual external representations provide information that can be directly perceived and used without being interpreted and formulated explicitly (Zhang 1997). Visual information representations function to support distributed cognition by engaging complementary cognitive subsystems. F1 said that the visual representation of information in the composition space enables the collection to be looked at in different ways. F4 said that visual representation is appealing, and makes connections of information are more apparent. Her group used the combinFormation composition for presenting their invention ideas, instead of PowerPoint.

Procedural generation of visual representations creates provocative stimuli in the form of the evolving composition space. F3 found that her group could overcome their limited space of ideas by seeing unexpected visual images. In creative cognition terms, the provocative stimuli of the procedural generation of the visual information representations helped them overcome fixation. M5 said that by combining and comparing multiple information elements generated in a composition space, he could develop ideas. This conceptual talkback, in which generated visual representations stimulate situated thinking and dialogue, constitutes the epitome of situated creative learning. As in Lave and Wenger's theory, "the notion of participation dissolves dichotomies between cerebral and embodied activity, between contemplation and involvement, and between abstraction and experience" (1991). The talk-back of the representation is the process through which the dichotomy dissolves. The generative visual composition medium of the prior work collection plays an essential role in distributed creative cognition, stimulating idea generation and idea refinement, individual reflection and social dialogue.

The messy juxtaposition of new elements of unexpected relevant information functions as a *preinventive structure* (Finke *et al.* 1992), a set of stimuli that provoke the creative exploration and cognitive restructuring of ideation. M2 said, "I organized and manipulated information elements in combinFormation to understand information. I developed and accidentally created ideas while I was manipulating elements." F1 added, "Through the process of making messy things organized, I came up with new ideas." The act of manipulating information elements in the composition space supports participants' creative processes, catalysing the emergence of new ideas. One example is the combinations of lights and jackets that helped Group 1 concretize their ideas. A similar effect came with the unexpected detail of 8 megapixels, juxtaposed with cameras and an iPod in the work of Group 2 (figure 7). In the distributed cognition of situated creative learning practice, the representation of the evolving mixed-initiative composition space supports the fluid evolution of social and conceptual relationships.

Creative learning tools need to represent learning materials in forms that match the cultural milieu of today's students. Today's young scholars have grown up with the Internet, cell phones, and video games. They are attuned to fluid, changing sensory stimuli. Participants appreciated the visual procedural generation of information on topics they find interesting The collection-as-composition's ensemble of forms and features was experienced as fun, promoting engagement and motivation.

Future research will continue improving understanding of and support for representations that externalize communication and ideation in situated creative learning and distributed creative cognition. We will develop better visual representations to better represent the ideas found in documents. The evidence indicates that this will increase engagement, as well as reducing cognitive load. Better information models, and retrieval and extraction algorithms will improve the quality of procedurally collected information. Developing new interactive methods for human manipulation will help participants work with increasingly large collections. Future evaluations of creativity support will again utilize the frameworks of distributed creative cognition and situated creative learning. To develop nuanced perspectives, we will combine laboratory experiments of information discovery with quantitative and qualitative field studies, using a validated measure of emergence (Kerne *et al.* 2007), as well as project grades, questionnaires, and interviews to collect data. We will consider other research task scenarios, such as thesis topic development. We will also work to extend data collection beyond the one semester of The Design Process course, to understand more about how digital information collection technologies can play a significant supportive role in the sustained activities, tasks, functions, and understandings of situated participant learners.

References

A.D. Baddeley, "Is working memory working?" *Quart J Exp Psychol*, 44A, pp. 1–31, 1992.

D. Bollier, *Ecologies of Innovation: The Role of Information and Communications Technologies.* Washington, DC: The Aspen Institute Communications and Society Program, 2000. Available online at: http://www.bollier.org/pdf/ecoinnov.pdf (accessed 22 October 2007).

C. Bonwell and J. Eison, "Active learning: creating excitement in the classroom", in *AEHE-ERIC Higher Education Report No. 1.* Washington, DC: Jossey-Bass, 1991.

J.S. Bruner, "The act of discovery", *Harv Educ Rev*, 31(1), pp. 21–32, 1961.

M. Burke, *Organization of Multimedia Resources*, Hampshire, UK: Gower, 1999.

R.N. Carney and J.R. Levin, "Pictorial illustrations still improve students' learning from text", *Educ Psychol Rev*, 14(1), pp. 5–26, March 2002.

M. Csikszentmihalyi, *Flow: The Psychology of Optimal Experience*, New York: Harper Perennial, 1991.

W. Ding, G. Marchionini and D. Soergel, "Multimodal surrogates for video browsing", in *Proceedings of ACM/IEEE Joint Conference on Digital Libraries*, 1999, pp. 85–93.

R. Finke, T. Ward and S.M. Smith, *Creative Cognition*, Cambridge, MA: MIT Press, 1992

A.M. Glenberg, "The indexical hypothesis: Meaning from language, world, and image", in *Working with Words and Images: New Steps in and Old Dance*, N. Allen, Ed., Norwood, NJ: Ablex, pp. 27–42, 2002.

A.M. Glenberg and W.E. Langston, "Comprehension of illustrated text: Pictures help to build mental models", *J Mem Lang*, 31(2), pp. 129–151, April 1992.

J. Hollan, E. Hutchins and D. Kirsh, "Distributed cognition: toward a new foundation for human–computer interaction research", *ACM Trans Comput Hum Interac*, 7(2), pp. 174–196, June 2000.

E. Horvitz, "Principles of mixed-initiative user interfaces", in *Proceedings of Computer Human Interaction*, 1999, pp. 159–166.

E. Hutchins, *Cognition in the Wild*, Cambridge, MA: MIT Press, 1995.

Interface Ecology Lab, *combinFormation*, 2007. Available online at: http://ecologylab.cs.tamu.edu/combinFormation/ (accessed 22 October 2007).

A. Kerne, "Doing interface ecology: the practice of metadisciplinarity", in *Proceedings of SIGGRAPH 2005, Art and Animation*, 2002, pp. 181–185.

A. Kerne, E. Koh, B. Dworaczyk, M.J. Mistrot, H. Choi, S.M. Smith, Graeber, R, D. Caruso, A. Webb, R. Hill and J. Albea, "combinFormation: A mixed-initiative system for representing collections as compositions of image and text surrogates", in *Proceedings of ACM/IEEE Joint Conference on Digital Libraries*, 2006, pp. 11–20.

A. Kerne, E. Koh, S.M. Smith, H. Choi, R. Graeber and A. Webb, "Promoting emergence in information discovery by representing collections with composition", in *Proceedings of ACM Creativity & Cognition 2007*, 117–126.

A. Kerne and S. Smith, "The information discovery framework", in *Proceedings of Designing Interactive Systems*, 2004, pp. 357–360.

A. Kerne, S.M. Smith, H. Choi, R. Graeber and D. Caruso, "Evaluating navigational surrogate formats with divergent browsing tasks", in *Proceedings of ACM Computer Human Interaction Extended,* 2005, pp. 1537–1540.

J. Lave and E. Wenger, *Situated Learning: Legitimate Peripheral Participation*, Cambridge: Cambridge University Press, 1991.

C.C. Marshall and F.M. Shipman, "VIKI: Spatial hypertext supporting emergent structure", in *Proceedings of European Conference on Hypermedia Technology*, 1994, pp. 13–23.

R.E. Mayer and R. Moreno, "Animation as an aid to multimedia learning", *Educational Psychology Review* 14(1), pp. 87–99, March 2002.

G.A. Miller, "The Magical number seven, plus or minus two: some limits on our capacity for processing information", *Psychol Rev*, 63, pp. 81–97, 1956.

K. Nakakoji, Y. Yamamoto, M. Akaishi and K. Hori, "Interaction design for scholarly writing: Hypertext representations as a means for creative knowledge work", *New Rev Hypermedia Multimedia*, 11(1), pp. 39–67, 2005.

D. Norman, *The Design of Everyday Things*, New York: Basic Books, 1988.

Oxford English Dictionary on Compact Disc (2nd ed.), Oxford: Oxford University Press, 1992.

Y. Rodgers, "Distributed cognition and communication", in *Encyclopedia of Language and Linguistics* (2nd ed.), 2004.

J. Rosenberg, "And And: conjunctive hypertext and the structure acteme juncture", in *Proceedings of Hypertext*, 2001, pp. 51–60.

J.J. Shah, S.M. Smith and N. Vargas-Hernandez, "Empirical studies of design ideation: Alignment of design experiments with lab experiments", in *Proceedings of DETC 2003: ASME 2003 International Conference on Design Theory and Methodology*, pp. 1–10, 2003.

H.A. Simon, "How big is a chunk?" *Science*, 183, pp. 482–488, 1975.

S.M. Smith, "Getting into and out of mental ruts: A theory of fixation, incubation, and insight", in R.J. Sternberg and J. Davidson (Eds), *The Nature of Insight*, Cambridge, MA, MIT Press, pp. 121–149, 1994.

G. Stahl, "Group cognition: The collaborative locus of agency in CSCL", *Proceedings of the 2005 Conference on Computer Support for Collaborative Learning*, pp. 632–640, 2005.

N.A. Streitz, J. Hannemann and M. Thuering, "From ideas and arguments to hyperdocuments: traveling through activity spaces", in *Proceedings of ACM Hypertext 1989*, pp. 343–364.

E. Tufte, *Envisioning Information*, Cheshire, CT: Graphics Press, 1990.

B. Wildemuth, G. Marchionini, M. Yang, G. Geisler, T. Wilkens, A. Hughes and R. Gruss, "How fast is too fast? Evaluating fast forward surrogates for digital video", in *Proceedings of ACM/IEEE Joint Conference on Digital Libraries*, 2003, pp. 221–230.

A. Woodruff, R. Rosenholtz, J. Morrison, A. Faulring and P. Pirolli, "A comparison of the use of text summaries, plain thumbnails, and enhanced thumbnails for web search tasks", *J Am Soc Inform Sci Technol*, 53(2), pp. 172–185, 2002.

I. Zhang, "The nature of external representation in problem solving", *Cogn Sci,* pp. 179–217, 1997.