

Student Management of Web-Based Hypermedia Resources During Open-Ended Problem Solving

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ABSTRACT Twelve middle school students' use of computer tools to manage and manipulate Internet-based hypermedia resources was investigated. Tools were proposed to support higher order thinking about hypermedia resources to help students find, frame, and resolve open-ended science problems. Tools alone were insufficient to help students manage hypermedia information for solving open-ended problems. Students more frequently applied lower order tool functions (e.g., information collection) than higher order tool functions (e.g., reasoning). Students typically resolved problems with original solutions, but tools were used infrequently to develop evidence-based arguments justifying new ideas. Computer tools alone may be insufficient to help students manage extensive hypermedia resources. Together with additional support structures, however, tool potential may be realized.

Key words: cognitive tools, constructivism, hypermedia, qualitative research, science education

Distinctions may be drawn between traditional and contemporary instructional models. Traditional models based on behavioral learning theory specify exactly what should be learned and how to provide instruction. For example, mastery learning models such as the audio-tutorial approach (Postlethwait, Novak, & Murray, 1972) and the personalized system of instruction (Sherman & Ruskin, 1978) advocate the use of technology systems to efficiently deliver information in top-down formats from the instructor's perspective. Teachers tell students what they should know, and students repeat that knowledge on a test.

Constructivists, in contrast, suggest appropriate tactics to facilitate learning as a more natural, authentic endeavor. For example, learning a foreign language via immersion in the native culture is considered more effective than unnaturally decomposing it through textbooks, vocabulary lists, and verb conjugations. Constructivists suggest that students learn best by structuring their own knowledge, rather than simply adopting the instructor's or textbook researcher's perspective. Several constructivists advocate the aid of technologies, including problem-based learning (Oliver & Omari, 1999), anchored instruction (Cognition and Tech-

nology Group at Vanderbilt, 1992), and cognitive apprenticeship (Collins, Brown, & Holum, 1991). To that end, students are asked to set learning goals, to seek and find relevant information to inform problems, and to communicate with peers to derive common solutions to problems (i.e., social constructivism).

In this research study, we used the constructivist model of open-ended learning. Self-directed learning and increased student responsibilities are tenets of open-ended learning (Hannafin, Hall, Land, & Hill, 1994; Land & Hannafin, 1997). Such environments do not teach facts removed from their context; they involve students in authentic inquiry (i.e., organizing resources, interpreting data, drawing hypotheses, representing information). Open-ended learning environments typically include four components: enabling contexts, resources, scaffolds, and tools (Hannafin, Land, & Oliver, 1999; Land & Hannafin, 1996). Internet-based hypermedia can provide realistic contexts and diverse resources to structure open-ended environments. *Hypermedia* refers to two or more information types (i.e., text, graphics, photos, video, audio) that can be linked electronically. The key concern with using hypermedia as the primary resource for open-ended learning is that existing Web browsers rarely scaffold learning. The multitude of available resources and links can confuse and disorient students, overload students cognitively, and interfere with the critical thinking required to solve open-ended problems.

In this study, we investigated the use of tools to help students collect, organize, annotate, and evaluate complex information during authentic science inquiry. We investigated the proposition that tools allow students to process hypermedia resources at higher levels to solve complex, open-ended problems. Higher order and critical thinking represent efforts to process and understand information through organization, synthesis, reasoning, and evaluation, rather than simply receiving and recalling factual informa-

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tion or procedures. Deep thinking is a goal of constructivist learning environments. (For taxonomies distinguishing higher order thinking from lower order thinking, see Bloom, Englehart, Furst, Hill, & Krathwohl [1956] and Marzano et al. [1991].)

Hypermedia in Open-Ended Learning Environments

Resources provide both information needed to solve open-ended problems and the substantive basis for the construction of artifacts. Although any resource can support open-ended learning, researchers recently experimented with Internet resources to support student inquiry (Edelson, Pea, & Gomez, 1996; Hannafin, Hill, & Land, 1997; Hill & Hannafin, 1997; Slotta & Linn, 2000). Internet resources are often realistic, extensive, inexpensive, current, accessible, and flexible.

Hypermedia boons and pitfalls. Researchers have questioned why network-like hypermedia should be used because learners understand logical hierarchical relationships more readily than network structures. Hypermedia helps to focus student attention on relationships rather than discrete facts, which assists learners in building accurate mental representations (Jacques, Nonnecke, & Preece, 1993; Kearsley, 1988). The “. . . nonlinear nature of hypermedia mirrors the structure of human long-term memory, lessening users' need to map from how computers represent data to how people store information” (Dede, 1992, p. 55). Furthermore, hypermedia can represent knowledge in multiple ways (i.e., audio, visual, spatial), support alternative points of view, provide realistic case studies involving different applications of the same knowledge, and cross-index concepts to promote cognitive flexibility (Jacobson & Spiro, 1995). Some researchers suggest that hypermedia promotes higher order thinking, such as evaluating the appropriateness of information (Dede, 1987; Marchionini, 1988).

On the other hand, hypermedia has been linked to problems in navigation and decision making (Jonassen, 1988; McKerlie & Preece, 1993). Students may experience difficulty navigating and locating needed information when hypermedia structures permit access and exit from multiple entry points (Hammond, 1992). Furthermore, individual decision making can be complicated when cognitive capacities are overtaxed by multiple options such as taking a quiz, participating in a discussion, or selecting supplemental text, video, audio, or animated sequences involving multiple links (Bruning, Schraw, & Ronning, 1995; Jih & Reeves, 1992). Hypermedia demands may be reduced after students are given some time to study and understand hypermedia structures. Then their focus can shift to hypothesis testing, knowledge integration, and learning rather than how to access materials and choose among options.

Nature of hypermedia tasks. Diverse opinions exist regarding students' use of hypermedia. Some researchers prefer structuring hypermedia via traditional instructional design models to present content to learners that can be

charted (Morariu, 1988). Others suggest exploratory approaches, allowing students to induct personal mental models by “. . . connecting concepts . . . forming interpretations, and synthesizing information” (Marchionini, 1988, p. 11). See also Hannafin & Land (1997) and Mayes, Kibby, & Anderson (1990).

In the present study, we used both didactic and constructivist approaches to hypermedia use. Students were first provided a core set of Web resources that established the foundation for the remainder of the study. Following the preliminary activity, during which students identified specific problems to resolve, they accessed a large database of Web sites from which they could choose to read, annotate, organize, or integrate additional evidence as they deemed appropriate.

Tools for Managing Hypermedia

Computer tools may help students to understand hypermedia relationships and to manage cognitive load (Hammond, 1992; Jonassen, 1992; Mayes et al., 1990; Search, 1993; Stanton & Baber, 1994). Hypermedia tool functions (see Table 1) are consistent with the classification scheme developed by Iiyoshi and Hannafin (1996). Some tools or tool sets will enable multiple functions. For example, the *VisIt* tool (Levin & Kauwell, 1999) allows learners to seek hypermedia information and to collect visual representations or “hits” of relevant Web sites. Representations are automatically organized in a cross-referenced display, or students may personally organize the representations into conceptual categories and integrate their impressions of the Web sites as pop-up notes. We selected the Knowledge Integration Environment (KIE) tool set for use in this study (Slotta & Linn, 2000). The various functions supported by the KIE tool set are outlined in Table 1.

Our primary research question was, “How do students use technological tools to find, frame, and resolve open-ended problems?” We sought to determine how students use tools to engage open-ended problems. The research proposition was one of human agency as described by Lofland and Lofland (1995, p. 183): “In *X*, people use strategies and tactics 1, 2, 3, *n*,” where *X* is open-ended problem solving with hypermedia resources.

Method

The research design was a qualitative, embedded case study, focusing on multiple units: classroom as whole (macro-unit), student dyads (intermediate unit), and individuals (micro-unit); see Miles and Huberman (1994) and Yin (1994).

Participants

We conducted this study at a rural middle school in the southern United States. Participants included 1 teacher and 12

Table 1.—Computer Tools for Hypermedia Management

Tool type	Example	Function	KIE Example
Seeking	Search engines, annotated resource lists, indexes, maps	Locating relevant information	Students can access key words and advance organizers for Web sites.
Collecting	Downloading, saving, bookmarking, cutting and pasting	Accumulating relevant information in accessible formats or locations	Save From Net tool allows student to collect external Web evidence.
Organizing	Constructing tables, charts, timelines, diagrams, and maps from existing information; VisIt (Levin & Kauwell, 1999)	Chunking two or more external information units with similar characteristics into a category, representing relationships	Sensemaker tool allows students to organize Web page links into categories to help understand various problems or theories (used in combination with Save From Net tool).
Integrating	Annotating or typing notes for information encountered; VisIt (Levin & Kauwell, 1999)	Merging external information with personal ideas, impressions, or conceptions	Mildred tool allows students to take notes on Web pages and respond to specific activity prompts.
Generating	HTML text editors; Web page generators; HyperAuthor (Lehrer, 1992); MediaText (Hay, Guzdial, Jackson, Boyle, & Soloway, 1994)	Creating a new conception based on information accessed	ClarisWorks tools; students could access this standard office package via their KIE interface to word process, draw, or use spreadsheets.
Manipulating	Simulations; StrathTutor (Mayes, Kibby, & Anderson, 1990)	Testing and revising a personal theory	None, but external simulations might be used if available for a particular study.
Communicating	E-mail; listservs; bulletin boards, video conferencing; CSILE (Scardamalia & Bereiter, 1996)	Stating and discussing a personal theory, ultimately revising and adapting to socially chosen norm	The SpeakEasy tool allows students to communicate in a discussion-board format.
Scaffolding	Instructions, advance organizers or annotations, elaborative links, strategic advice	Receiving procedural, conceptual, or metacognitive guidance related to a specific task	Students access instructions, conceptual prompts for Web pages, and metacognitive hints.

Note. KIE = Knowledge Integration Environment.

eighth-grade students divided into six dyads. The teacher grouped students into heterogeneous dyads by ability, defined by individual reading scores on the seventh-grade Iowa Test of Basic Skills (ITBS). Emphasis was placed on comprehension because reading was critical to engaging the hypermedia resources. Initially, 1 high-ability student was paired with each low-ability student. Because of an argument among the students, 4 of them were reassigned by the teacher, resulting in one low-low and one high-high ability group.

Participant selection was purposive rather than random because it represented a group likely to require technological scaffolding to solve open-ended problems with hypermedia resources. Results of an anonymous survey of students in 3 eighth-grade classes at the school, including the case study class, indicated that only 14 of 56 students accessed the Internet at home and only 8 of 56 used the Internet in their school. Few students had previous experience with hypermedia resources. Furthermore, most students lacked experience with open-ended problem solving. When surveyed about how they used computers in their school, most students indicated that they used them to write papers, type, or conduct background research. No students described using computers to solve any type of problems. Eighth-grade classes were selected for this study because

that is a group likely to require tools to think creatively and critically with unfamiliar hypermedia resources. Typical eighth graders are developmentally close to Piaget's formal operational stage in which their ability to develop hypotheses and think logically is emerging (Carey, 1985).

The Open-Ended Problem Activity

Students were asked to find, frame, and resolve open-ended design problems involving building collapse during earthquakes. Earthquake engineering involves addressing a variety of interconnected problems (e.g., column design, roof design, soil strength). Students also were asked to select and resolve one such problem. Common themes across creative and general problem-solving models suggest that inductive, open-ended problem solving involves (a) selecting relevant issues to focus on (identify or find a problem); (b) developing categories, concepts, and relationships (represent and frame the problem); and (c) proposing evidence-based hypotheses or implementing strategies to test a solution (resolve the problem; Bransford & Stein, 1993; Bruning et al., 1995). The inquiry process of participants was not entirely open ended, but it was structured with project activities reflecting this framework.

To help students find engineering subproblems, we asked the students to access and read 13 preselected Web sites. The researcher (the first author) and classroom instructor selected the Web sites on the basis of their ability to concisely overview the diversity of earthquake engineering problems for students. All Web sites were downloaded and placed on computers in the school laboratory because the research site did not yet have Internet access. An advance organizer preceded each Web site to help students integrate the new information more readily (Ausubel, 1963). The screens contained (a) questions to prompt students, (b) key words to search for, and (c) annotations of the more detailed content to follow, to help students focus on problems associated with earthquake engineering. One advance organizer asked the following:

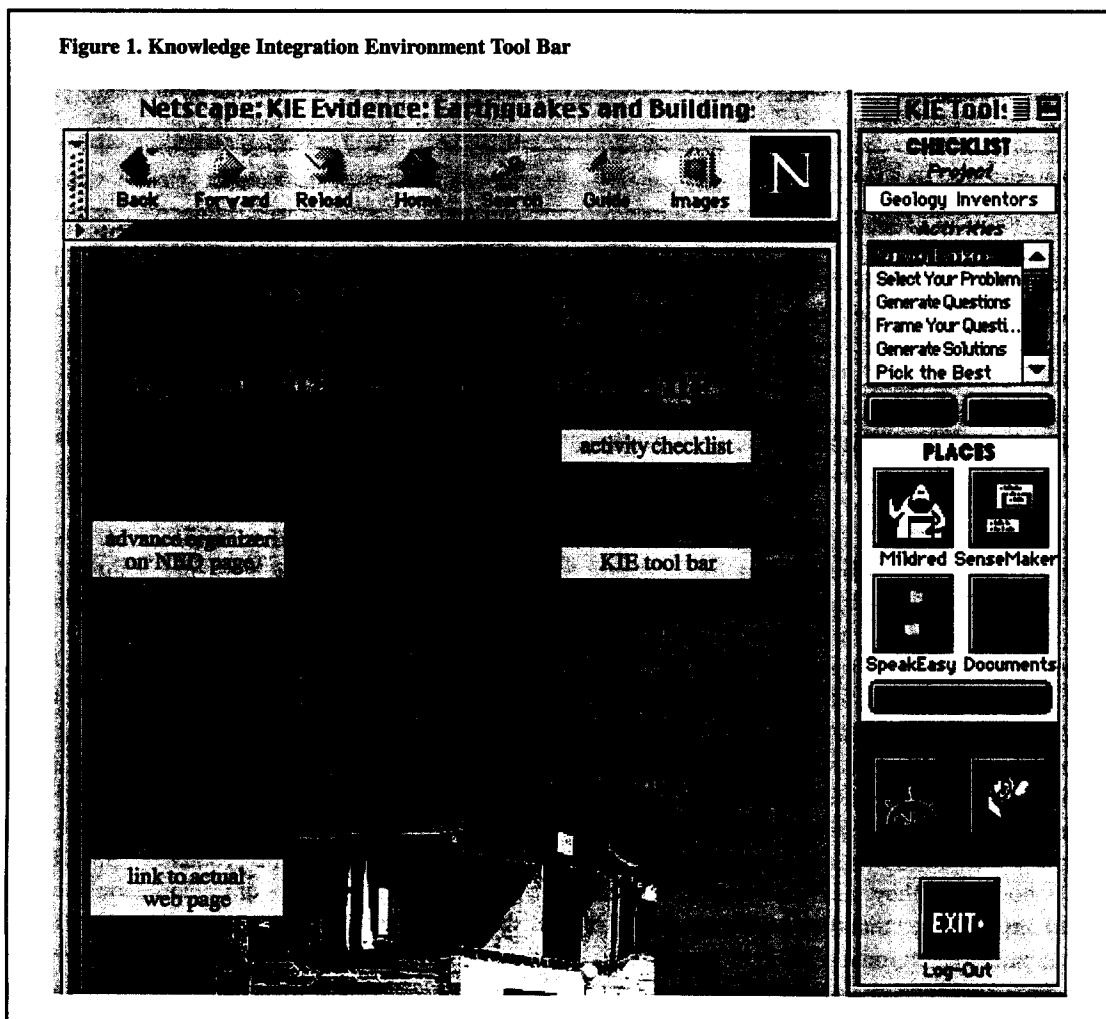
As these pictures from the 1979 Montenegro earthquake illustrate, roofs that are not connected in some way to the columns or poles that support them, could slide off in an earthquake and fall. Click on the hyperlinks below to find out more. What type of bracing might have prevented this from happening?

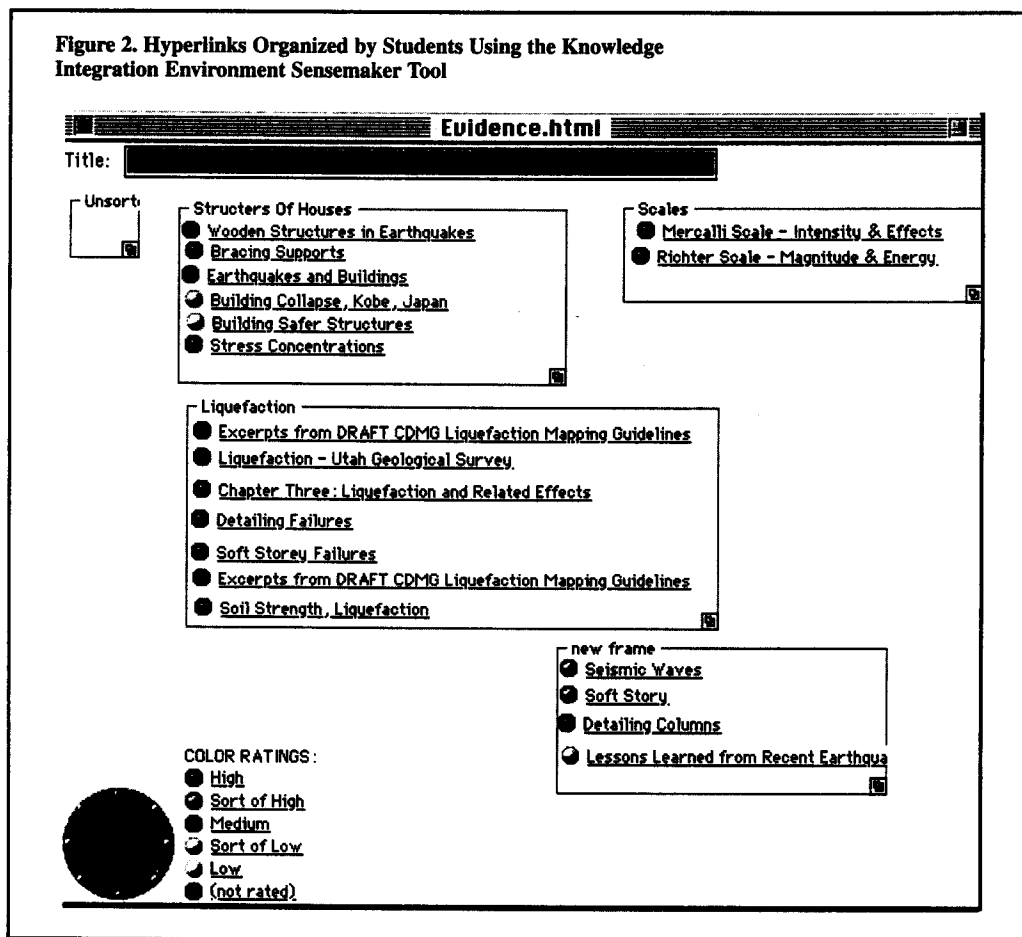
After students selected one problem to resolve from the collection of problems described on the 13 Web sites, we asked

them to generate research questions to further guide their inquiry during a problem-framing stage.

The problem-framing stage provided time for students to collect and organize information related to their selected problems. Rather than hastily suggesting solutions to their selected problems, we asked the students to critically reason for several potential solutions using evidence found during problem framing. To facilitate problem framing, we provided an additional 65 Web sites and 46 books and articles related to earthquake engineering topics. Those items also were selected by the researcher and teacher on the basis of their ability to provide an adequate, supplemental perspective on each earthquake engineering problem introduced through the 13 original Web resources. The additional resources were not annotated or organized systematically by problem type, which required the students to browse, read, and extract relevant information. Students were asked to find information that would inform their research questions.

After students answered their questions, they were asked to brainstorm potential solutions. To facilitate that problem-solving stage, we provided an evaluation template for students to rate and select their best solution. The form described how to evaluate and then select appropriate solu-





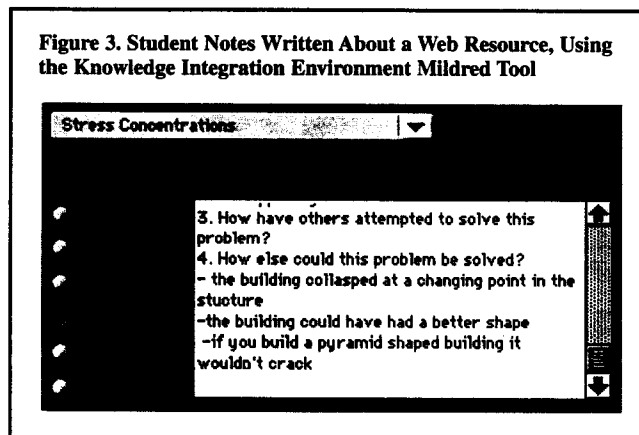
tion ideas (e.g., consider cost, time to build, social impact). Students were then asked to generate design drawings and an experiment plan to test their final solution choice. Finally, students generated Web pages to share, discuss, and defend their ideas during 2 days of classroom presentations.

Materials

We chose the KIE computer tools for use in this study. KIE contains multiple tools designed to support student scientific inquiry with hypermedia resources (Slotta & Linn, 2000). The tools were chosen over others (Laffey, Tupper, Musser, & Wedman, 1998; Edelson et al., 1996; Ryan & Koschmann, 1994; Suthers, 1996) because they contained the greatest variety of tools (see Table 1), which included multiple-scaffolding tools needed by the participants. The tools were provided courtesy of a National Science Foundation project; features could be used at the offline research site and logistical support was available from the developers. Figure 1 illustrates KIE's tool bar alongside a student's Web browser.

The Sensemaker tool allowed students to organize the 13 original Web pages into problem-related categories during problem finding (see Figure 2). Students could draw and label boxes representing categories of earthquake engineering problems (e.g., columns, soil quality, building materials), then sort the 13 hyperlinks by dragging them under

proper headings. During problem framing, the Save From Net tool allowed students to collect and place new hyperlinks on their Sensemaker diagrams. That feature helped students integrate additional Web evidence to support or contradict a particular category. Integration was supported with a note-taking tool called Mildred (see Figure 3), which allowed students to write notes and record responses for specific activities (e.g., generate research questions). Using the KIE tool bar, students also could open the ClarisWorks and Netscape Gold software programs. ClarisWorks supported information generation by allowing students to cre-



ate drawings for their solution ideas. Netscape Gold also supported information generation by allowing students to create Web pages describing their thinking and explaining their solution ideas to others.

Students could access procedural scaffolding to determine what to do for each activity and how to do it by clicking the Details button on the KIE tool bar. For example, the following advice was available for the first project activity:

1. What to do: Read through the "core set" of evidence. Try to understand the many different reasons why buildings collapse.
2. How to do it: Click on the "home" button in Netscape to open up the core set of evidence. Decide with your partner how you will keep track of information described in the core set of evidence.

Additional procedural guidance was provided by a series of handouts describing how to use the tools and produce artifacts (e.g., how to use Sensemaker, how to create a Web page with Netscape Gold). To access handouts, students clicked the button labeled Documents on the KIE tool bar. Students were also provided conceptual scaffolding in the form of advance organizers preceding the 13 original Web pages and through hints provided via the Mildred tool. An example of a conceptual hint prompted students to consider, "Why do wooden structures collapse during earthquakes?" Students also could receive metacognitive scaffolding in Mildred. Those scaffolds helped learners to think about what they knew and did not know, which strategies were available, and when strategies should be employed. One strategic prompt in Mildred provided the following advice:

You've created many solutions that may be useful to solve your earthquake problem. Now you need to "get real" and pick the solution that is best or most likely to be used in solving your earthquake problem. The solution rating form may help you do this by focusing you on many important ideas. For instance, how much would it cost to implement your solutions? If it costs too much, then it probably shouldn't or couldn't be used. Be realistic and pick the best option.

KIE also included a communication tool named SpeakEasy. That tool allowed students to discuss problem issues or debate solution plans online, but we did not use it in this study because of limitations in the computer network at the research site.

Procedures

Research procedures were divided into prestudy pilot and training sessions, the actual research study, and follow-up activities.

Training. The 5-week research study was preceded by a 4-week pilot study and a 2-day training period. The researcher and teacher were present throughout all three activities and shared training responsibilities. Each session during the pilot, training, and research study lasted approximately 50 min.

The pilot study was conducted to test research instruments

and methods for their ability to elicit salient data. Similar methods were used during both the pilot and research studies with only minor additions to interview protocols following the pilot. During the pilot study, students were trained on tool use and introduced to basic plate tectonic concepts in a theory comparison unit titled Geologic Land Formation. The unit involved student debate of two conflicting theories: catastrophic earth change versus "uniformitarian" earth change. Students selected the theory they believed to be true, developed arguments with the support of Web evidence, and shared their ideas with the class by developing and presenting a Web page. The pilot study directed students to use all KIE tools explicitly (e.g., "Use Sensemaker to sort all of your Web evidence into categories"). That rule was to ensure that each student knew how to use the tools. We sought to determine how or if students voluntarily elected to use tools to satisfy their own intention, so it was important to establish their tool awareness and proficiency. During the research study, the researcher and teacher asked students to work through each project activity, but they did not require students to use tools to collect, organize, or annotate information or to evaluate original ideas.

A 2-day training project was held approximately 3 weeks after the pilot study and prior to the research study to reintroduce the KIE tools. We presented a series of basic activities and explicitly instructed students to use all of the available tools. Each student worked alone on a computer, providing individuals with the opportunity to ask questions about the tools, practice and recall their skills with the tools, and learn how to use the tools in the event that they did not use them during the pilot study.

Research study data collection. Students read through the 13 original Web pages during the first week of the research study, after which they were tested to determine how much information they extracted from their varying tool use. At the end of the study, students repeated the same test. During each class period, observations of tool use, student participation, and environmental influences were documented as field notes. Artifacts were collected three times during the study upon completion of each phase—finding, framing, and resolving. That method was used to document the evolution of students' products as they evolved every 3–4 days on the basis of tool use. The eight artifacts collected are outlined in Table 2.

Each dyad also was interviewed three times, coinciding with the completion of problem finding, framing, and resolving activities; they were asked to reflect on their processes during each phase. The researcher also asked students about tool use issues as they emerged (e.g., "I've noticed you aren't using Sensemaker . . ."). The interviews were recorded on audiotape and transcribed. Electronic project folders contained student artifacts, allowing the researcher to use projective techniques during qualitative interviews. Students were asked to reflect on their artifacts and thinking to assess the utility of their tool use (Goetz & LeCompte, 1984; Savenye & Robinson, 1996). For instance, students were

Table 2.—Eight Artifact Data Sources

Artifact	Description
Research questions	During problem finding, all students wrote science questions as activity notes with their Mildred tool to guide them strategically in searching for specifics.
Selected evidence	During problem framing, some students selected additional Internet evidence using Save From Net and off-line resources.
Evaluation forms	In their Documents folder, students could choose to fill out information quality evaluation forms to help evaluate self-selected Internet evidence.
Argument graphs	Students could choose to use their Sensemaker tool to sort and categorize original and self-selected Web evidence.
Notes	Students could use their Mildred tool to record notes on evidence and to describe solution options.
Design drawings	Students were asked to use ClarisWorks to create design sketches for their inventions.
Testing plan	Students could use Mildred to write testing plans for their inventions.
Web page presentation	Students were asked to use Netscape's Web page editor to create Web pages that would be used to present their ideas to others.

asked, "Here are the notes you wrote this week; did recording notes help you find a problem to focus on?"

Follow-up activities. Following the study, all students completed four trials of an "ordered tree" technique to determine how well (or if) they could organize study concepts related to earthquakes and earthquake engineering (Reitman & Rueter, 1980). To extract an ordered tree, students arrange terms on a list by relation. The ordered tree technique allows student understanding to be compared with an expert model; more important, personal models or categorization schemes can be analyzed individually. Patterns of thought were identified over multiple trials with the terms differentially arranged. Following the study, students also responded orally to new

problems. That assessment posed a hypothetical, open-ended problem and asked students to describe the steps they would take and the tools they would use to solve it.

Analysis

The analytical strategy used in this case study sought evidence confirming or disproving the following theoretical proposition (Yin, 1994): If students use computer tools to manipulate hypermedia resources in a manner consistent with higher order creative and critical thinking (e.g., organize, integrate, evaluate), they will effectively solve open-ended problems. We sought evidence related to students' intentional use of tools, the thinking exhibited, and the ability to find, frame, and resolve their selected problem. Confirming or disproving that hypothesis situates the research within the analytic induction tradition that seeks "... continual refinement of hypotheses" until the data of the case are accurately depicted (Merriam, 1998). Unlike grounded theory, which starts with raw data and builds to theory, this study began with theory and built toward more focused theory. A modified theory for student tool use was derived following an analysis. The analysis consisted of three concurrent phases: coding and reduction, display and pattern seeking, and interpretation and verification (Miles & Huberman, 1994).

Coding and reduction. Much of the data collected in this study underwent pattern matching or typological analysis (Lecompte & Preissle, 1993) that involved using a "... start list of codes" early in data analysis (Miles & Huberman, 1994, p. 58). Student thinking through tool use was compared with critical and creative thinking codes developed by other researchers (Ennis, 1991; Marzano et al., 1991; Newman, Webb, & Cochrane, 1995). Codes from those existing typologies and new emergent codes were inserted into a database. FileMaker Pro was used to manage study data. We extracted 1,095 data clips from all data sources (e.g., interviews, student artifacts) and merged them into a database. Several fields were filled in—group or individual responsible for the clip, tool involved in the

Figure 4. FileMaker Pro Database Used to Code and Sort Data Sources

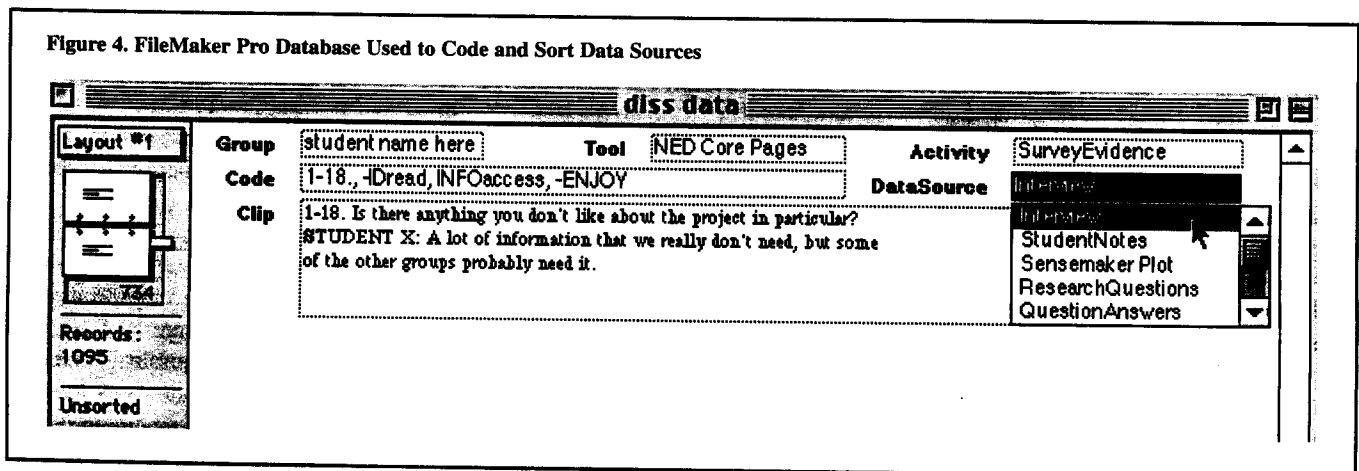
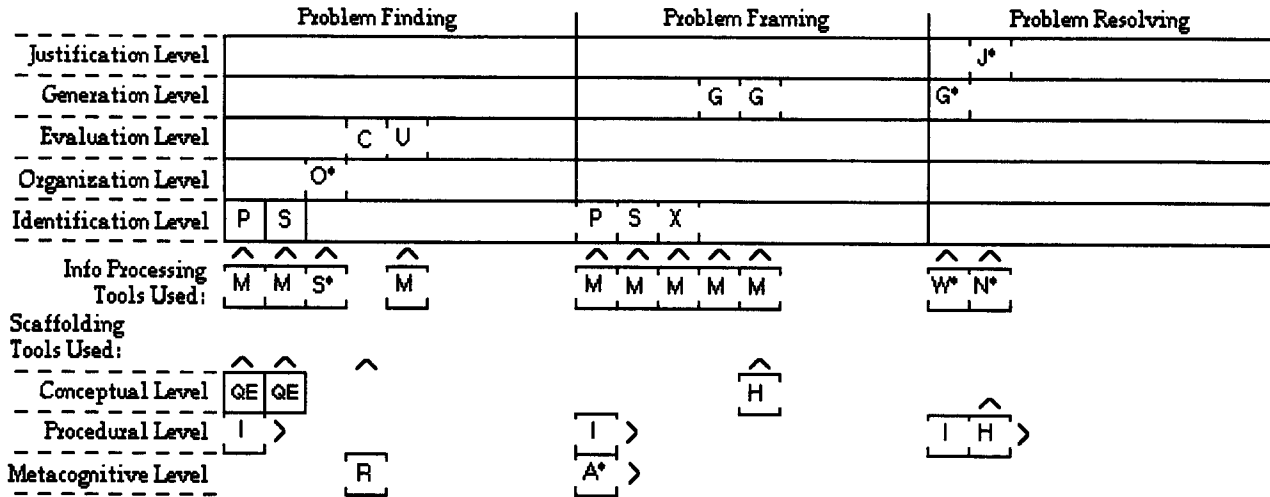


Figure 5. Sample Thinking Matrix From One Dyad

Methodical Dyad: Tool Use to Thinking Diagram**Thinking Key (higher-order to lower-order):**

J = justification, G = generation, U = evaluation of understanding, C = evaluation of content, O = organization, X = identify patterns, R = identify problem restrictions, P = identify premises, S = identify solutions

Tool Key:

(Information Processing) M = Mildred, S = Sensemaker, W = ClarisWorks, N = Netscape Gold

(Scaffolding) Q = question prompts, E = evidence hints, A = activity hints, H = handouts, I = instructions, R = rating

^ = single activity use
> = cross-dimension use

* The diagram depicts all coded instances of thinking, however low-quality tool use and thinking are marked with an asterisk.

creation of the clip, activity during which the clip was created, data source from which the clip came (e.g., interview), and qualitative codes (e.g., student identifies premise; see Figure 4).

Using the database, we searched for and sorted all codes by activity and tool. That process resulted in categories of thinking associated with activities and tools (e.g., organizing evidence during problem framing with the Sensemaker tool). Certain types of learning, specific attitudes and behaviors, and environmental barriers also were associated with various activities and tools (e.g., dislike expressed for extensive reading during problem finding). When confirming or disconfirming instances were identified across dyads, we performed categorical aggregation suggested for case study analysis to extract specific instances from the database and to record them in a detailed text (Creswell, 1998; Stake, 1995). Disconfirming instances also were described to help explain why thinking skills did not emerge from tool use (e.g., few students use evaluation forms). While sorting and developing the aggregated text, we developed higher level categories to explain how dyads used tools, what types of thinking and learning were related, and whether tool usage was effected by attitudes or environmental impacts. For instance, while recording instances of two micro-codes in the aggregated text, rushed behavior and limited infor-

mation identification through self-directed searching, we noted shared properties that suggested a category (i.e., attitudinal or behavioral impacts on tool use). Categories were described as pattern codes.

Display and pattern seeking. Although aggregated texts help to identify some patterns, they tend to be sequential and bulky (Miles & Huberman, 1994). To facilitate further pattern seeking, the aggregated text was read in detail for all instances of thinking and tool use. Those instances were displayed in several checklist matrices, partially ordered by the three study dimensions (Miles & Huberman, 1994; see Figure 5 for a sample matrix). Five general categories of critical thinking were displayed and the aggregated text was reviewed for instances that fit into the categories.

We also compared the thinking that each tool was designed to support with the thinking that was actually demonstrated. We based that comparison on when particular tools could be used to document disconfirming instances of tool use and thinking (e.g., students could be using the Save From Net button during problem framing to integrate new Web evidence into their Sensemaker diagrams). If tools were not used at certain stages to accomplish expected ends, then we recorded a disconfirming code.

In addition to thinking blocks within the matrix, tool blocks also were placed below the matrix. If the data sam-

Table 3.—Dyad and Individual Descriptors

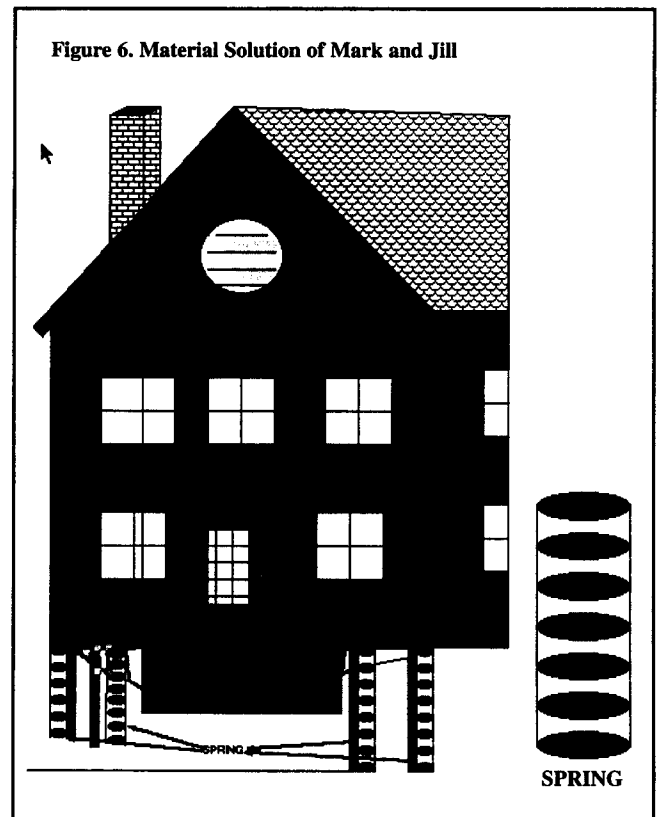
Dyad and individual	Ability level	Tool use	Solution quality	Content learning	Liked group
1					
Edie	High	Reluctant to use tools	Unoriginal but relevant	Average	Yes
Jenny	High	Reluctant to use tools		Average	Yes
2					
Mark	High	Rushed use of some tools	Original but irrelevant	Average	No
Jill	Low	Used only generation tools		Minimal	Yes
3					
Nate	High	Limited tool use	Original and relevant	Exceptional	No
Keith	Low	Limited tool use		Above average	Yes
4					
Gena	Low	Used most tools	Unoriginal but relevant	Average	—
Gary	Low	Used only generation tools		Above average	Yes
5					
Ruth	Low	Used most tools	Original, partly relevant	Above average	Yes
Jared	High	Used most tools		Above average	Yes
6					
Randy	High	Used most tools	Original and relevant	Exceptional	No
Tisha	Low	Used few to no tools		Minimal	Yes

ple that suggested a thinking skill (e.g., information evaluation) was created by an information processing tool (e.g., Mildred) or potentially influenced by a scaffolding tool (e.g., question prompts), additional square blocks were placed directly under the thinking block. The tool blocks illustrated which tools were associated with the data sample's creation, suggesting possible relationships between the tools and thinking. When higher order thinking was evident but led to incorrect assumptions, we recorded an asterisk to ensure that tools were not credited for supporting better thinking. New categories were generated by studying the matrices for commonalities in thinking (e.g., "The first dyad rarely used metacognitive scaffolding, did the second, did the third . . . ?"), a process consistent with discriminant sampling (Lincoln & Guba, 1985).

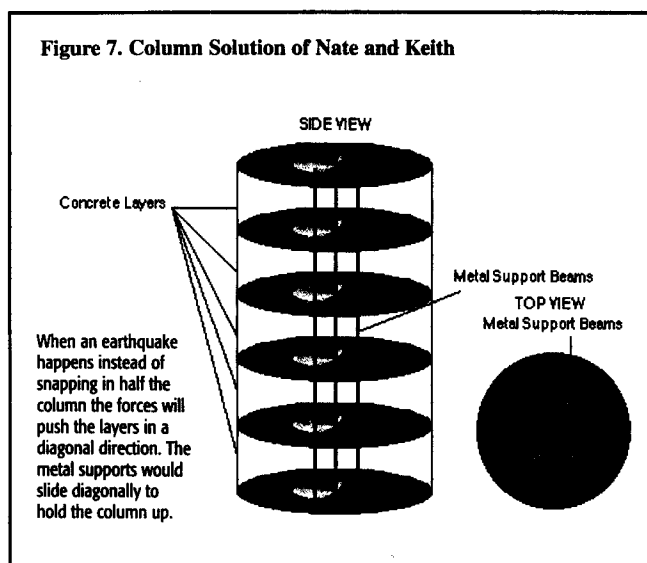
Once micro-codes were sufficiently sorted into higher level categories or pattern codes, they were compared to determine ". . . how units are like and unlike each other" (Lecompte & Preissle, 1993, p. 242). Similar categories were grouped to create tool use themes such as inclusions ("X is a kind of Y"), cause-effects ("X is a cause of Y"), and means-ends ("X is a way to do Y"; Spradley, 1979). For example, if lack of scaffolding use and lack of Sensemaker use are both evidence for lack of intentional tool use, we asked if any other categories supported this theme.

Interpretation and verification. The study findings were interpreted and verified by considering other data sets; further verification was provided by exposing the findings to colleague review as suggested by Miles and Huberman (1994). First, the researcher reviewed the literature on tool use and thinking to seek confirming or disconfirming results once categories and themes were developed. Recent research on tool use was reviewed from doctoral dissertations and other completed studies (e.g., Grant, 1994; Laffey et al., 1998; Myers, 1993). Second, during 2 summer months fol-

Figure 6. Material Solution of Mark and Jill



lowing the study, we participated in an online community of teachers and researchers who used KIE tools in other studies. The community was initiated by the tool developers to discuss issues of using their tools in school settings. As categories and themes were suggested by analysis, many of these ideas were posted to the community via an online, threaded discussion tool. Some responses of other KIE tool users to the researcher's findings provided verification and



further context for our results and conclusions. Those individuals also used the KIE tools in middle school settings and in several instances corroborated the present findings.

Dyad Profiles

Findings are arranged by dyad profiles and case themes that were found to cut across dyads. Table 3 provides individual and dyad descriptors. The following three case themes are presented last: student extraction of basic hypermedia information; lower order thinking through processing tools; and scaffolding support for questions of how, but not what or why.

Dyad 1: Edie and Jenny

Edie and Jenny, both high-ability students, worked well together socially but rarely functioned as a problem-solving team. For example, the students were observed reading separate Web pages during problem finding rather than discussing the resources together. Jenny made critical project decisions, such as creating the team's solution drawing, without Edie's help. Edie and Jenny engaged their problem with little intention, their interest seemed low, and they generated minimal artifacts to represent their understanding. They also generated the fewest original solutions after problem framing. They selected both materials and shapes as earthquake engineering problems to resolve rather than focusing on one specific topic. Their final solution was a wooden structure shaped like a pyramid that was relevant to resolve both problems selected, but unoriginal, because Web resources made similar suggestions.

Dyad 2: Mark and Jill

Mark and Jill did not work together as a problem-solving team, but they accepted independent, complementary roles.

Mark, a high-ability student, carried out most of the processes to generate a solution (e.g., note taking) and was able to clearly state where the group received their information: "... we looked at bookmarks and additional evidence." Jill, a low-ability student, hesitated: "I don't know, he took me in there . . ." Jill worked with tools more during the creative problem-resolving stage. At that time, she worked to generate Web pages, whereas Mark did not participate. The two students rarely discussed their project or solution ideas together. Mark and Jill rushed their work, generated simple artifacts for their activities, and gathered only limited evidence to inform a relevant solution. That dyad misapplied some of the tools provided. For example, they were one of only two dyads that did not organize the 13 original Web sites with Sensemaker. They selected materials as their earthquake problem. Their final solution was a house on springs, which was original, but somewhat unrelated to presented evidence describing earthquake-resistant building materials (e.g., wood and steel superstructures in place of masonry; see Figure 6).

Dyad 3: Nate and Keith

Nate (high ability) and Keith (low ability) worked well as a team. They were observed discussing their problem on several occasions and comparing their individually created design drawings. Nate and Keith used scaffolding less than the other dyads. They relied on their own abilities and memories. The pair asked few questions, were self-guided, and adequately resolved the problem they chose. Both students worked hard during the study and exhibited little off-task behavior. It was difficult to determine how much thinking was exhibited by that dyad because their artifacts, especially notes, were limited. They used few tools, but were one of only two dyads to create both an original and relevant final solution—a hybrid steel and concrete column using equally spaced steel discs to offset earthquake forces (see Figure 7). They were also one of only two dyads that provided written advantages on their Web pages that explained why their solution was more appropriate than other solutions.

Dyad 4: Gena and Gary

Gena and Gary, both low-ability students, rarely worked together as a team. Gena was outgoing, talkative, and expressed interest in the project; Gary was quiet and appeared bored. Gena completed most of the note taking, sorting, and development work with the tools, although Gary was able to describe how the group used tools when queried during subsequent interviews. Gena and Gary struggled from the outset to find a relevant problem, then rushed through problem finding and framing. They captured less information than any other dyad with Mildred's note-taking screen. They were the only dyad that failed to describe premises or proposed solutions for building collapse during problem finding. Further, they were one of two dyads who did not generate new solution ideas during prob-

lem finding. The pair selected bracing as their earthquake problem; they resolved it with a relevant but unoriginal solution—a simple steel brace across roof lines.

Dyad 5: Ruth and Jared

Ruth and Jared worked together more effectively than other dyads. Both indicated on their tool use surveys that they liked group work. They were observed discussing the project together on several occasions. When generating solution options, Jared (high ability) was overheard asking Ruth (low ability), “. . . weren't these columns steel bracing” and “. . . so how could you improve that?” Ruth was searching through her Web pages while Jared recorded solution ideas in Mildred's note-taking screen. They also discussed different solution possibilities while completing the rating form.

Ruth and Jared worked through each activity using most of the tools. They spent more time than most groups framing their selected problem but rushed to finish the remaining activities. They identified and recorded the most premises for causes of engineering failures during problem finding and framing, and were the only dyad to generate written predictions as notes during framing. They were also the only group to use the metacognitive scaffolding information evaluation form. Not surprisingly, they generated more original solution ideas than any other dyad. Ruth and Jared selected bracing as their earthquake problem. They resolved the problem with an original, partially relevant final solution—an hourglass-shaped building with external bracing. Their awkward design shape was flawed and contradicted Web evidence suggesting inherent weaknesses in such designs. The students were one of only two dyads, however, to provide written advantages on their Web pages justifying why their solution might be more appropriate than other solutions.

Dyad 6: Randy and Tisha

Randy (high ability) and Tisha (low ability) did not function well as a team. Few instances were observed when both students were present and collaborating because Tisha was absent during most of the project. One day when both students were present, Randy worked on design drawings while Tisha did little at her computer. Randy worked alone to both create artifacts and give his group's presentation. He selected shapes of buildings as his initial earthquake engineering problem, then later began to study liquefaction. Randy resolved his second problem with both an original and a relevant solution—a floating house with ballast to promote stability.

Case Themes

Theme 1: Student Extraction of Basic Hypermedia Information

The first theme reflects the considerable time that students spent collecting and describing basic information

about earthquake engineering problems. One category suggested that students were able to extract basic information from a small set of hypermedia resources when conceptually prompted to find specific items. A second category suggested that students found less information when required to search through a larger database with less conceptual guidance. In both cases, however, students identified only basic information such as premises and solutions. As shown in Table 4, students rarely considered restrictions on the problems or described patterns across the data.

Conceptually scaffolded searches. Students were most successful in identifying information during problem finding. They all surveyed the 13 Web pages describing various engineering problems and recorded core evidence in response to question prompts that scaffolded the activity. Despite the availability of advance organizers and evidence hints, students rarely proceeded beyond the prompts provided to integrate their own thoughts and reactions or to describe patterns.

The first conceptual question prompt asked students to consider the following: “What is the problem described by this evidence?” We designed the prompt to help students think about the underlying causes of engineering design flaws (i.e., premises). Five of six dyads identified four or more relevant premises from the core Web pages, suggesting they were able to extract specific underlying causes of engineering failures from the Web evidence. For example, one premise identified by Ruth and Jared was, “It is better to have a less flexible roof during an earthquake.” Nate and Keith wrote, “. . . complicated designs of corners of buildings caused them to be weak and collapse.”

The second conceptual question prompt asked, “Why would this problem be difficult to keep from happening?” Students rarely moved beyond basic information identification to consider restrictions or to ask why it would be difficult to avoid the engineering problems. An example of correctly identifying a restriction given by Nate and Keith was, “Lots of older buildings have wooden supports and it is hard to change the support material.” No dyad correctly identified more than two restrictions from the core Web pages.

The third conceptual question prompt asked, “How have others attempted to solve this problem?” and was designed to help students examine existing solutions in order to build

Table 4.—Basic Information Identification Across Study Phases

Variable	Finding	Framing	Resolving
General information summarized (IDsum)	15	0	0
Premises identified (IDpr)	29	19	6
Solutions identified (IDSol)	12	19	5
Restrictions identified (IDrestrict)	9	1	7
Patterns identified (IDpat)	4	5	2

on, modify, or improve their designs. An example of identifying solutions was provided by Ruth and Jared: "The best way so far to solve this problem is to keep the designs of buildings simple, boxlike. . . ." Solutions were not outlined on all core Web pages, which contributed to minimal solution identification during problem finding.

Self-directed searches. During problem framing, students were asked to answer their own research questions. Conceptual questions and prompts were not available for individually selected problems. Students were given 65 additional Web pages and several print-based resources to search for information related to their selected problems. Most students simply skimmed the information. For instance, Jared said, "Some of the articles are long, and we can't read every word of it or we'd take too long, but we can scan over it and find the basic information."

Most dyads used key words as they browsed additional Web evidence, seeking information to frame their selected problems. For example, Edie and Jenny said they used key words such as wood and steel to find information related to their materials topic. Some students became quickly overwhelmed by searching for too many topics. For example, Randy listed his key words and indicated that he was trying to frame too many problems rather than one specific issue: ". . . design, soft story, liquefaction, detailing, just stuff that, it didn't all go under ground shaking, but they probably [said] something about liquefaction." The teacher described how some students limited their key word searches to document titles, suggesting they did not actually read the Web page content to identify relevant information: ". . . some of them aren't willing to search through the page. They look at the title, and if the title doesn't have the word 'detail' or 'column,' they don't even look at it." With those search strategies, the dyads identified premises and solutions, but, again, few restrictions.

Interpretation. Basic information collection appears to be mediated by the size of the resource bank, the degree to which a student's search task is scaffolded, or a combination of both. It is possible that students extract more information from fewer resources, as during problem finding using 13 Web pages, but it is uncertain if the conceptual question prompts influenced this outcome. Unsuccessful data gathering during problem framing might have improved if students

were provided conceptual guidance. Instead, they were asked to answer their own research questions that may have been inappropriately focused given their limited prior knowledge about earthquake engineering.

Student questions were evaluated using criteria applied in a previous KIE study (Slotta & Linn, 2000, pp. 216–217). The criteria that we used included (a) Was the question specific to a component of the selected problem? (b) Was the question relevant to some aspect of the selected problem so its answer would help inform that problem? (c) Was the question productive and likely to lead to an experiment? Students were provided metacognitive scaffolding via Mildred for writing scientific questions. As shown in Table 5, most student questions met the relevance criterion, but few questions were specific. Specific questions indicated that students understood underlying variables in their problems and focused their search on pertinent information (e.g., "Will a building constructed of both wood and steel material withstand a P-wave?"). Rather, students asked many nonspecific questions focusing on their entire problem. For example, Mark and Jill asked, "What materials are best?" Furthermore, most student questions did not generate a question that might suggest an experiment (Slotta & Linn, 2000). Productive questions, such as hypotheses or predictions, could focus student inquiry on specific data to prove or disprove an assumption. Only two dyads generated productive questions.

Theme 2: Lower Order Thinking Through Processing Tools

Tools were provided to scaffold higher order thinking, but students rarely used them. According to the checklist matrices created mainly from student artifacts, the predominance of lower order codes suggests that few students used tools to organize information, seek patterns of relationships in the data, specify solution plans, justify ideas, or defend solutions. Interview data were used to corroborate those assumptions; students described their tool use in lower order or nonintentional capacities.

Organization of hypermedia information. During problem finding, four of six dyads used Sensemaker to organize hypermedia into problem categories; however, few students used their organizational schemes as a basis for selecting a connected problem. For example, Ruth and

Table 5.—Nonspecific, Relevant, Nonproductive Research Questions

Criterion	Specific	Nonspecific	Relevant	Nonrelevant	Productive	Nonproductive
Edie, Jenny		5	4	1		5
Mark, Jill		4	3	1		4
Nate, Keith	1	4	5		1	4
Gena, Gary	1	2	3			3
Ruth, Jared	1	4	5			5
Randy, Tisha	1	2	2	1	1	2
Total	4	21	22	3	2	23

Jared created one problem-related topic heading, “. . . soil,” but selected a problem of bracing buildings for which they had no categories. In addition, students could use the Save From Net button during problem framing to integrate additional Web evidence into their Sensemaker categories. New evidence could be used as the basis for supporting or modifying categories. Yet, only Randy attempted to integrate additional Web evidence within his core Web evidence categories: “I tried to put in some extra [links] that could’ve helped [cause the shapes problem], like liquefaction could have helped. . . .” Student attempts to organize hypermedia are a focusing technique, helping them to find categories of problems, determine critical components of problems, and visualize how problems relate to other problems or issues. The task is critical to clarify problem-related issues and to induct a viable solution that addresses most or all mediating factors.

Generation of designs. Students were asked to create design drawings during problem resolving, but the task failed to elicit much higher order thinking about solution ideas. Students suggested mostly that the drawing tool was helpful procedurally. For example, Gena said, “It’s better than drawing it out freehand, ‘cause it draws the shapes and everything for you.” Information generation tools such as Web page generators or drawing programs could help students synthesize data or justify their solutions by describing advantages, disadvantages, or comparisons to other ideas. Only two dyads, however, used the drawing tool to explore how their designs might address their problem. Drawing tools should help students visualize and modify their ideas. Randy stated, “[My idea] probably did [change], on some things, something more floatable or lighter to keep the house up.” Jill noted the following:

It made us think of a lot more than we would need to think about because like, we were just like, “we’ll put the springs on the house.” but you had to see like, how are the springs going to help out something.

The thinking skill, evaluation, might be elicited more appropriately by manipulation tools that allow students to test the resistance of their design to various earthquake motions. Static visualization may be less effective than dynamic and revisable modeling.

Justification of solution paths. During interviews, students were asked which resources and tools helped them to justify their solutions. Students typically referenced a single Web resource, indicating their solution ideas were developed on the basis of limited evidence. Four dyads said Mildred should help them to support their ideas mostly because it contained their notes. Students did not describe, however, how Mildred could help defend their solutions with a large collection of supporting evidence. None suggested that Sensemaker helped them to organize relevant evidence; few suggested that Netscape helped, even though it allowed them to link to supporting evidence, provide illustrations of an idea, or describe advantages of an idea. With Netscape, half of the dyads used hyperlinks to index additional evi-

dence, although links were not used to justify or defend students’ ideas (e.g., “click here to see a Web page that agrees with part of our solution”). For example, Nate said Netscape was useful “. . . mostly so I can make something else to connect [my web page] to, so it’s a bit longer. . . .” Only two dyads went beyond describing solutions on their Web pages to justify why they were better than other solutions. Ruth and Jared wrote, “Some buildings have such a design that bracing is not needed as much. Our solution was to make an hourglass shaped building. We thought this would help because it wouldn’t need as much bracing as some other buildings.”

Tools have the potential to support higher order thinking by allowing students to reflect intentionally on and integrate their opinions and questions in logs (synthesis, evaluation) or to cite supporting and contradictory evidence in Web-based presentations (justification). Higher order potential, however, does not guarantee that students will use tools with higher order strategies. Intention is likely attributable to both the realization that higher order thinking is needed to solve an open-ended problem (i.e., cognitive experience), as well as the motivation to actively resolve an interesting dilemma. Scaffolds for student strategies and interests may be essential to augment tool use (Hannafin et al., 1999).

Theme 3: Scaffolding Support for Questions of How, But Not What or Why

Students used considerable procedural guidance, but very few conceptual or metacognitive hints. In addition, they rarely used scaffolding tools to engage in higher order evaluation of either hypermedia resources or their own ideas.

Procedural scaffolding employed most frequently. Most students used KIE’s procedural scaffolding during the problem finding, framing, and resolving dimensions of the project. Conceptual scaffolding was employed less frequently. Although students responded to conceptual question prompts in Mildred, they rarely accessed conceptual evidence to focus on key concepts in the core Web pages. Randy noted, “I didn’t really use the hints, I can’t find any use for those . . . mainly try to work and get the main stuff done.” In addition, few students indicated that they read the metacognitive activity hints in Mildred. For instance, Jared said, “We haven’t looked at those as much, but they’re still useful if we ever need something like that.”

Students may have had difficulty completing the study activities without following procedural instructions, or perhaps they expected to be told explicitly what to do. They may have used procedural instructions because they were explicit, prescriptive, and directive and used evidence and activity hints with declining frequency because they were only suggestive. One activity hint suggested, “When looking for additional information to solve a problem, it is often useful to look for ways in which other people have tried to solve the problem.” The goal of that hint was to encourage students to look for preexisting solutions. If students failed

to understand why that task was important, they might have ignored it and proceeded to the next activity.

Metacognitive evaluation tools misapplied. Mildred provided a metacognitive scaffold to rate the content of core Web pages; five of six dyads used it. Only two dyads, however, seemed to rate the evidence according to its content. Ruth and Jared rated two evidence pages describing the Mercalli and Richter scale as low, whereas they rated all other evidence as high. The Mercalli and Richter evidence was not related directly to earthquake engineering and building collapse, so students may have perceived inapplicable content. Three other dyads did not use the rating tool to evaluate information. For example, Mark was observed haphazardly rating the entire list of core Web pages in approximately 5 min near the end of the survey evidence activity.

Two evaluation forms were used infrequently during the study. Only Gena used an information evaluation form that provided criteria to evaluate the quality of hypermedia information. She indicated that her group used the form to guide them, but the students never completed it. To help students evaluate their different solution ideas and select the best solution option, we provided a solution rating form. Most students used the form, but few based their final solution on criteria. When asked if her group used the rating form, Jenny replied, "I used it, but I didn't really need it, because I already knew what I was going to do." The teacher commented as follows on student reluctance to base decisions on criteria:

I think with the solution evaluation, they had already made up their mind before they did the form, of which design they wanted to choose . . . regardless of cost, or how society would accept the design, they had decided that this was actually neat and I like it best and I can draw it so that's what I'm going to use regardless of how realistic [it is].

The data suggest that middle-grade students are reluctant to use criteria to evaluate information, their metacognitive processes, and their ideas. They appear confident in their abilities to ascertain the legitimacy of evidence and to generate solutions without suggested criteria. By failing to heed tool-based scaffolds, students make naive assumptions, overlook multiple problem perspectives, and fail to validate their ideas or elicit alternative views.

Modified Proposition for Tool Use

We sought evidence to confirm or disprove the following proposition: If students use computer tools to manipulate hypermedia resources in a manner consistent with higher order thinking (e.g., organize, integrate, evaluate), they will solve open-ended problems. The weight of evidence suggested that tools supported mostly low-level information gathering and thinking. Students only partially solved open-ended problems using solutions on the basis of limited evidence and rife with misconceptions. The proposition was not supported because students did not use tools to their full

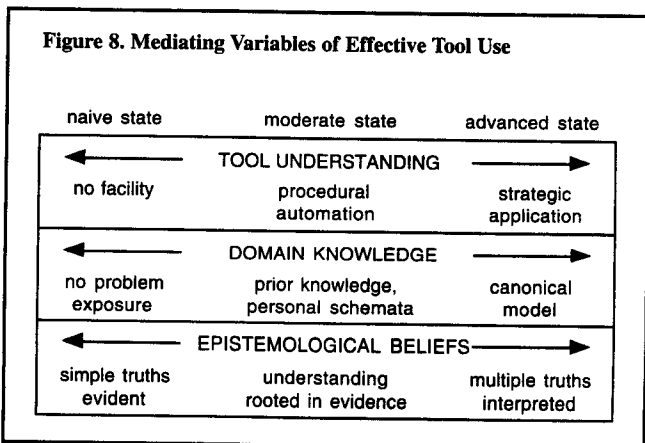
potential; nor was it refuted. Students might engage in higher order thinking if tools are used effectively.

On the basis of the study findings, we modified the proposition to first explain why tool use may be ineffective—lack of facility with tool features and tool strategies, limited knowledge about problem-related concepts, and naive epistemologies or beliefs about learning and strategy (see Figure 8). Each of those variables exists along a continuum from a naive state to a more advanced state, and student facility exists at different points along these continua. For example, students with advanced domain understanding may have only limited tool understanding. Furthermore, the variables are not necessarily discrete. A student with advanced domain knowledge might overcome limited tool understanding to solve an open-ended problem; limited domain knowledge and tool understanding, however, might severely limit problem-solving ability. In the following sections, the progression of tool facility, knowledge of problem concepts, and epistemology are described along with findings from the present study.

Emergence of Tool Understanding

Procedural tool understanding is prerequisite to strategic application. Knowing how to use a tool does not guarantee that students will know when and why to employ it; it is a necessary, although not sufficient, condition of effective tool use. Hay, Guzdial, Jackson, Boyle, and Soloway (1994) found that students unfamiliar with their MediaText multimedia composition tool tended to create compositions less integrated with media than those more familiar with the tool. As experience increased, students integrated more media with their compositions. In novel situations, students tend to rely on familiar processes rather than to experiment with new tool features designed to extend the student's initial capabilities (Hay et al., 1994).

When tool functions are not fully automated, cognitive resources may be allocated disproportionately toward operating tools, rather than applying them. For example, students in this study struggled procedurally to generate Web pages using Netscape. They asked many questions about



how to make Web pages, but few questioned why Web-page construction was important. Their focus was on producing pages rather than on cultivating the reasoning process. Even when procedural facility is gained, it does not ensure that students will use tools strategically. All study participants generated solution designs with ClarisWorks, but few elaborated the features of their solutions. Typically, student solutions contained many misconceptions that were recognized only via peer questioning during final presentations.

Students were not prompted to reflect on the strategic implications of tool use during training. It was assumed that they would interpret the strategic implications of tool use by working to resolve a complex, open-ended problem. The in-context training may support procedural tool use in the short term but may not support strategic tool understanding. To support both tool procedures and their strategic use, the teacher suggested that the students use tools longitudinally across multiple grades, bridging to open-ended projects in later grades. She said

What I would like to see in the school is 6th grade try it, introduce it, 7th grade use it, 8th grade use it, and they get it every year, then by 8th grade they would be exposed enough that they could use these tools for critical thinking skills, and you would get a much better project. We wouldn't have to spend so much time on making sure they knew that Sensemaker was a very good organizational tool, they would know how to use it, they would know what it could do for them.

Although considerable time and practice may be requisite to appropriate tool use, a proactive teacher or capable student peer can facilitate the process by modeling tool use and prompting students to use tools strategically.

Emergence of Domain Knowledge

Students with limited domain knowledge likely find it difficult to use tools strategically. They might find it difficult to seek and collect appropriate problem-related information or to organize and synthesize problem-related information. In this study, some participants experienced difficulty narrowing the macro-context of earthquake engineering to specific connected problems; others were unable to focus questions about the problems.

The use of communication and hypothesis testing tools in particular may help students with limited domain knowledge to develop more advanced conceptions of problem topics. As student understanding about problems evolves, their use of other tools may improve (e.g., realizing the need to rename categories or reorganize evidence in Sensemaker; realizing the need to seek and collect further information about a specific problem). Flexible tools should allow students to continually revise artifacts as problem understanding gradually improves.

Communication promotes problem understanding. For design problems such as earthquake engineering, Perkins, Goodrich, Tishman, and Owen (1994) suggested that teachers and peers can help students to activate existing knowledge via classroom discussion. In this study, participants

clarified their understanding of earthquake engineering problems during classroom presentations and follow-up questioning. After presenting their solutions, dyads often were confronted by peers with different ideas about similar problems. Through peer review, the students were forced to consider flaws in their reasoning—a thinking level rarely obtained through the tools employed. Whereas most students ignored tool-based scaffolding during the study, they acknowledged their peers who asked questions during debates and presentations (e.g., explain your answer, provide evidence to support that idea). Communication tools and in-class discussions are useful supplements to electronic scaffolds alone.

It may be fruitful to use communication tools or in-class discussions to encourage students to think about life experiences related to unfamiliar problems like earthquake engineering. Harel and Papert (1993) conducted research on students using Logo programming software to teach other students about fractions. As the project progressed, students developed more advanced models for fractions by representing them as everyday objects with the programming tool (e.g., clocks, measuring cups, airplanes). Some participants in this study used familiar objects as part of their solution drawings—the placement of trampolines under buildings and the use of hair “scrunchies” in columns to promote flexibility in earthquakes. The teacher described the following conversation between herself and a student who used a familiar idea as an analogy for a more elaborate solution:

One of the students was saying, “Well you know how the ear balances the person, it helps to keep your balance, you could use that in a sense, on top of the building, use large tanks of water, and when they're not being used to balance, they could be used as a coolant system, as a recycling coolant system or heating system.” He was talking about those wave machines that go back and forth, and when the wave hit, the water would slosh way to the other side of the building, the constant weight idea, that was quite a unique and interesting idea.

Hypothesis testing promotes problem understanding. A recurring issue in open-ended problems is the inability or unwillingness to consider a range of potentially valid models or solutions (Johnson-Laird, 1990). Using tools that allow for rapid prototyping of many models, learners can manage and manipulate more models than short-term memory typically allows (Wild, 1996). Manipulation tools such as simulations allow students to test personal theories, receive immediate feedback, contemplate discrepancies in their hypothesized versus resulting outcome, then reformulate and test a new model accounting for the difference (Land & Hannafin, 2000). Incorrect models are eventually shaped toward more canonical models. Whereas students developed original designs inductively in this study, manipulation tools were not employed to test ideas or visualize forces. Tools that facilitate model revising might have influenced understanding of earthquake problems. For instance, students who elected to resolve the liquefaction problem could have used a program to study the strength of different soil types during earthquakes of varying magnitudes.

Snir and Smith (1995) found that students who simply draw scientific models can be led to generate rules explaining complex scientific phenomena (e.g., weight and density). When simulations are used, however, nearly all students generate rules to explain data (e.g., the rate at which an object sinks depends more on its density than its weight). Although manipulation tools alone may not help students solve open-ended problems completely, they may scaffold intermediate procedures within the larger complex process (Crews, 1995).

Emergence of Epistemological Beliefs

Students with limited exposure to open-ended problem solving may have a limited capacity to recognize valid strategies from invalid ones. Those with naive epistemological beliefs typically use tools less effectively than experts. For instance, if students believe open-ended problems can be quickly resolved without referencing problem-related evidence, they may not collect or strive to integrate data; if they believe simple solutions can resolve complex problems, they may not employ manipulation tools or experiments to test and formatively revise their ideas. Students who accurately perceive the complexity of open-ended problem solving and who focus on problem-solving processes may use tools more strategically.

Perceptions of demand influence tool strategy. Tools may be ineffective if they do not correspond with perceived task demands. Kozma (1992), for instance, found that advanced students used different scaffolding than did novice students. Novices used scaffolding and tools that matched their simple perceived demands of a writing task (i.e., generating content). Advanced students used scaffolding and tools that supported the perceived complex demands (i.e., contemplating rhetoric and audience). In the present study, students used procedural scaffolds extensively as well as some conceptual scaffolding but ignored many metacognitive prompts. Students did not heed metacognitive advice prompting them to consult multiple sources of evidence in framing their problems. Most students suggested that the scant information gathered was sufficient to inform their complex problems.

If students do not understand the importance of tools, educators may need to model tool use strategies. Educators should not simply provide tools that meet the perceived demands of their novice students; educators should encourage students to consider deeper application of information (e.g., illustrating the value of Sensemaker for organizing hyperlinks and visualizing relationships) to change students' perceived task demands. The cognitive apprenticeship model developed from situated cognition theory provides a framework for scaffolding student use of unfamiliar tools (Collins et al., 1991). Teachers model, then coach, students on relevant strategies, gradually fading the scaffolds as students gain expertise (Beed, Hawkins, & Roller, 1991). Students may exhibit better scientific inquiry when specific feedback related to their tactics is provided (McGee, 1996).

Product orientations influence tool strategy. During interviews, participants described their problem-solving processes and the information they encountered. In many cases, neither the strategies nor the information was documented by tool use. That fact might suggest that students believed that their final products were important, but not their interim processes or products. A product orientation might influence students to inappropriately use evaluation forms and other tools that encourage the formative development of ideas. For instance, few study participants used rating forms to evaluate and to modify their ideas, and few revised their ideas while sketching with ClarisWorks. Similarly, students in a study by Carver, Lehrer, Connell, and Erickson (1992, p. 395) ranked the design task of "getting someone to try out the presentation" and evaluate their ideas among the least important tasks.

Although product-focused tactics might be naive for open-ended learning, they might be considered refined in settings that emphasize products of learning. Tobin, Tippins, and Hook (1995) found that students were reluctant to adopt a constructivist approach to abandon traditional approaches with which they were more familiar. Laffey et al. (1998) suggested that some students may view tools as mere representational vehicles for creating artifacts, not devices that support inquiry. Such beliefs may be particularly difficult to change unless students are exposed to many activities or projects that stress formative processes. The teacher noted the following:

Well, I just think that with these kids, this particular group, and it seems to get worse and worse every year, they're not critical thinkers, unless they're asked to do activities and projects and problems that enforce critical thinking skills.

If students from traditional schools exhibit naive beliefs that can interfere with appropriate tool use, scaffolding more appropriate strategies may be critical. For example, Dunbar (1993) found that students tasked with generating hypotheses, rather than finding information to inform them, developed new predictions to account for the inconsistent evidence they encountered. During problem finding and framing, participants were asked to collect evidence to inform their problems. In this study, the strategy of finding evidence often did not lead students to apply evidence to their problems. Perhaps students could be asked to generate hypotheses or formulate rules when evidence consistent with their beliefs is detected (e.g., brick buildings collapse during earthquakes), then generate alternate hypotheses or rules when inconsistent evidence is found (e.g., only brick buildings without external bracing collapse during earthquakes; Land & Hannafin, 1996). Those tasks might help students to use tools more analytically (e.g., seeking patterns across data sources) rather than to confirm personal theories.

Conclusions

We investigated how tools support student thinking about hypermedia resources while solving open-ended problems.

Our findings did not provide evidence that tool use supported higher order thinking, nor did they refute that possibility. Open-ended learning environments require an integrated combination of tools, resources, and scaffolds as well as a well-formulated, enabling context (Hannafin et al., 1999). Hypermedia resources alone, even highly relevant resources, are insufficient for students to solve an open-ended problem. Students will likely require tools to support organization, synthesis, analysis, and evaluation of information contained in hypermedia databases.

Still, tools may not support the functions for which they are intended if students do not possess the metacognitive awareness to apply them strategically. Students may benefit from training in strategic tool use or modeling of tool-enhanced problem solving, as well as specific activities or tool mechanisms to help them communicate and hypothesize about open-ended problems. That combination of scaffolding and tool support may help students to develop more advanced epistemological beliefs and to ultimately apply tools more strategically toward understanding and resolving complex, open-ended problems.

NOTES

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The results of this study were based on student intention to use tools and may not represent the tools' full potential if combined with complete classroom scaffolding as suggested by the modified study proposition.

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VOLUME 94 NUMBER 2 NOVEMBER/DECEMBER 2000

- 66 It Says in The JER . . .
- 67 Effect of Part-Time Work on High School Mathematics and Science Course Taking
Kusum Singh and Mehmet Ozturk
- 75 Student Management of Web-Based Hypermedia Resources During Open-Ended Problem Solving
Kevin Oliver and Michael J. Hannafin
- 93 Parents' Conceptions of Kindergarten Readiness: Relationships With Race, Ethnicity, and Development
Karen E. Diamond, Amy J. Reagan, and Jennifer E. Bandyk
- 101 Effects of Within-Class Grouping on Student Achievement: An Exploratory Model
Yiping Lou, Philip C. Abrami, and John C. Spence
- 113 Effect of Difficulty Levels on Second-Grade Delayed Readers Using Dyad Reading
Alisa Morgan, Bradley R. Wilcox, and J. Lloyd Eldredge
- 120 Understanding Middle Students' Beliefs About Knowledge and Learning Using a Multidimensional Paradigm
Marlene Schommer-Aikins, Wei-Cheng Mau, Susan Brookhart, and Rosetta Hutter
- 128 Among Those Present

80th Year of Publication Dedicated to the Study of Education