An Analysis of Cognitive Tool Use Patterns in A Hypermedia Learning Environment

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Abstract

This study examined the use of cognitive tools provided in a problem-based hypermedia learning environment for sixth-graders. Purposes were to understand how the built-in tools were used and if tool use was associated with different problem-solving stages. Results showed that tools supporting cognitive processing and sharing cognitive load played a more central role early in the problem-solving process whereas tools supporting cognitive activities that would be out of students' reach otherwise and hypothesis generation and testing were used more in the later stages of problem-solving. The findings also indicated the students increasingly used multiple tools in the later stages of their problem-solving process. The various tools, performing different functions, appeared to enable students to coordinate multiple cognitive skills in a seamless way and, therefore, facilitated their information processing. Results also suggested that students with higher performance scores seemed to have made more productive use of tools than students with lower performance scores. Findings of the study are discussed.

(Keywords: cognitive tools, tool use pattern, problem-based learning, hypermedia technology, problem-solving)

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In their book, Bransford, Brown, and Cocking state that the educational goals for the twenty-first century are very different from the goals in the past: "Society envisions graduates of school systems who can identify and solve problems and make contributions to society throughout their lifetime…" (2000, p. 133). This goal requires our students to be good problem-solvers, critical thinkers, and lifelong learners. The development of such higher-level thinking skills may be best achieved by way of a learning environment that is student-centered, knowledge-based, and mirrors real-life complexities (Bransford et al.). To help students succeed in such a learning environment, different levels of support must be provided. Technologies, if used appropriately, can help provide some of that support by bringing real-world problems into the classrooms through multimedia and internet capabilities; and providing scaffolding to augment what learners can do (Bransford et al.).

When technologies are used to assist students' learning and problem-solving, they become cognitive tools, holding the potential for helping establish effective learning environments. Cognitive tools are instruments that can not only guide learners' cognitive processes, but also amplify cognitive functioning and extend human minds (Pea, 1985). Such cognitive tools should be of particular assistance to young and novice learners who are still in the process of developing their higher-order thinking skills. While there is a strong belief that cognitive tools can support and extend cognitive processes of a learner, there is little empirical research to substantiate this notion (Iiyoshi & Hannafin, 2002). Research is needed to empirically verify such assumptions and examine if the tools are used as intended.

The purpose of this study was to investigate the actual use of cognitive tools provided a problem-based hypermedia learning environment designed for sixth graders. Problem-based learning (PBL) is an instructional approach that emphasizes solving complex problems in rich contexts and aims at developing higher-order thinking skills (Savery & Duffy, 1995). Because student-centered learning environments like PBL are typically complex and ill-structured, there is a need to build in technology support in the form of cognitive tools to enhance PBL delivery. This study examined how the built-in cognitive tools were actually used and if the tool use was associated with different problem-solving stages and students' performance.

Theoretical Framework

Cognitive tools are computer-based tools that can amplify and enhance human cognition, and can serve as partners in cognition to extend human intelligence (Pea, 1985; Salomon, Perkins, & Globerson, 1991). Cognitive tools are instruments that can not only guide learners' cognitive processes, but also amplify cognitive functioning and extend human minds (Pea, 1985). In discussing factors that could inhibit learning such as limited capacity of work memory, difficulty in retrieving needed information from long-term memory, and ineffective use of cognitive strategies to restructure information, Kozma (1987) suggested using computers to facilitate the learning process and assist learners in accomplishing complex cognitive tasks. He believed that computers could provide such aids as making large amounts of information immediately available for use to supplement limited short-term memory, enabling learners to retrieve prior knowledge and apply it more efficiently in a new situation, and allowing learners to represent ideas in multiple forms. Jonassen (1996) defined cognitive tools as, "computer-based tools and learning environments that have been adapted or developed to function as intellectual partners with the learner in order to engage and facilitate critical thinking and higher-order learning" (p. 9). He mentioned hypermedia authoring and spreadsheets as examples of cognitive tools that help students externalize their knowledge.

Lajoie (1993) examined the various design features of instructional software currently available and categorized the cognitive tools into four types according to the functions they serve: (a) tools support cognitive and metacognitive processes; (b) tools share cognitive load by providing support for lower-level cognitive skills so that resources are left for higher-order thinking skills; (c) tools allow learners to engage in cognitive activities that would be out of their reach otherwise; and (d) tools allow learners to generate and test hypotheses in the context of problem solving. She (1993) described a hypermedia learning environment, Bio-world, in which cognitive tools were incorporated to enhance high school students' argumentation process, allowing students to form diagnostic hypotheses and collect evidence to confirm or disconfirm their diagnoses. For example, students could consult an online medical library to access a database of medical knowledge during their problem-solving and the program would respond with both textual and visual representations of medical terms, concepts, and processes. By automating tasks students typically complete with the use of lower-level cognitive skills, such as performing routine diagnostic tests, Bio-world allowed students to focus on interpreting test results in the context of their diagnosis. In Bio-world, students could also consult the expert opinions of physicians, which provided contextually relevant assistance to the students. In short, cognitive tools are instruments that can enhance the cognitive powers of learners during their thinking, problem-solving, and learning (Jonassen & Reeves, 1996; Kozma, 1987; Pea, 1985; Salomon, Perkins, & Globerson, 1991).

Literature indicates that learners typically have difficulty managing complex problem-solving tasks (Hawkins & Pea, 1987). Cognitive tools are of particular importance in a problem-solving situation in that they can scaffold problem representations. Adequately representing the problem to be solved is a key to problem-solving (Jonassen, 2003). By means of internal and external representations, cognitive tools can guide the conceptualization and interpretation of a problem by revealing relationships among concepts and attributes (Zhang, 1997; Zhang & Norman, 1994). According to Zhang (1997), external representations are the knowledge and structure in the environment, while internal representations are the knowledge and structure in memory. A student's internal representation of a problem, and the information provided through an external representation, together create a distributed cognitive task (Zhang & Norman, 1994). This distribution of representations influences a student's processing of information. External representations are not simply inputs and stimuli to the internal mind, but are so essential to cognitive tasks that they can anchor and structure cognitive behavior (Zhang & Norman, 1994). In the context of using cognitive tools as a form of external representation, the design of cognitive tools can allow the elements of a problem to productively interact, and hence facilitate learners' processing of the problem (Sweller & Chandler, 1994).

Although researchers have identified the benefits of using cognitive tools, there is a lack of empirical research investigating specifically how cognitive tools influence students' information processing. How are tools actually used? Are tools associated with various problem-solving stages they are intended to support? "We need to better understand the use of multiple tools" (Iiyoshi & Hannafin, 2002, p. 835).

As our first step in our program of research to assess the scaffolding cognitive tools can provide in a PBL hypermedia environment, this study examined the actual tool use patterns to understand the relationship between the use of cognitive tools and sixth-graders' problem-solving process. Two research questions of this study were:

1. How are the built-in cognitive tools used in relation to the problem-solving process the sixth graders are engaged in?

2. Are there any differences in tool use patterns for students in high and low performance groups?

Method

Sample

Participants were 110 sixth-graders from a middle school in a mid-sized southwestern city. Of these students, about 9% (*n*=10) were in the Talented and Gifted (TAG) classes, and 13% (*n*=14) were identified as students needing additional academic help, students who speak English as a second language or have learning disability (ESL/LD). Approximately 78% of the students (*n*=86) were in regular education classes (RegEd), and 45% of the students were female (*n*=50). Most students had used computer programs such as games and word processing programs prior to the study. Two teachers taught the six participating sixth-grade science classes. Sixth-graders were chosen as the research sample because they were the target audience of the PBL environment used in this study.

A PBL Hypermedia Environment

In this study, Alien Rescue, a hypermedia PBL program designed specifically for sixth-graders (Liu, Williams, & Pedersen, 2002), was used as the science curriculum in a three-week period. Guided by the theories and research on problem-based learning in its design, the goal of Alien Rescue is to engage sixth-grade students in solving a complex problem that requires them to gain specific knowledge about both our solar system and the tools and procedures scientists use to study it. The software is CD-based, and designed for approximately fifteen 45-minute class sessions. It begins with a video presentation of an ill-structured problem for students to solve. A group of six species of aliens, different in their characteristics, have arrived in Earth orbit, due to the explosion of their home planets. They must find new homes that can support their life forms or they will die. Students, acting as scientists, are asked to participate in this rescue operation, and their task is to determine the most suitable relocation site for each alien species. To solve this problem, students must engage in a variety of problem-solving activities. They need to research the aliens' needs as well as planets in our solar system to find possible new homes. Students must also engage in planning and decision-making as they determine how to use the resources of the solar system effectively. More information about Alien Rescue can be found on its web site, http://www.alienrescue.com.

To assist the students, a set of cognitive tools is provided to scaffold students' problem-solving. Table 1 provides a summary of the function of each tool. These tools are available through a two-layered interface in Alien Rescue. The first layer is the virtual space station itself, which consists of five rooms, each containing an instrument for students to use. From the center of the space station, students can navigate to any room by using the arrow keys on their keyboard. These rooms are the conference room (serving as the starting point for navigation), the research room which houses the alien database, the probe builder room where probes are designed, the launcher room where probes are launched, and the control room where new information gathered through launched probes is displayed (see Figures 1 and 2 for screen shots). The second layer of the interface, a retractable overlay, consists of a collection of tools. This overlay lines the sides and bottom of the screen. These tools are available to the students wherever they go from room to room through the imaginary goggles they are wearing. Students simply click on a tool to access it. This overlay contains tools such as the notebook, bookmark feature, solar system database, mission database, concepts database, charts, messages and experts (see Figures 1 and 2).

-------------Insert Table 1 here------------

-------------Insert Figures 1-2 here--------

Using Lajoie's categorization (1993), these tools can be grouped into four categories: (a) tools that share cognitive load, (b) tools that support cognitive processes, (c) tools that support cognitive activities that would be out of reach otherwise, and (d) tools that allow hypotheses generation and testing. Examples of tools that share *cognitive load* in Alien Rescue are the four databases. These are carefully constructed and well-organized knowledge databases enhanced through graphics, animations, and 3-D videos. If students want to know what a species looks like, where they live, the atmosphere and gravity on a planet, or past NASA missions, they can find such information readily in the alien database, solar database, and mission database. If they come across a scientific concept with which they are unfamiliar, they can look it up in the concepts database that provides visually illustrated tutorials on various science topics. Such tools help reduce the memory burden for the students and put the multimedia-enriched information at students' fingertips. An example of a tool supporting *cognitive processes* is the expert tool. Presented in the video format, the expert is available at four critical points to model expert thinking process in solving the central problem. Examples of the tools supporting *cognitive activities that would be out of reach otherwise* are the probe builder and launcher rooms. They allow students to equip probes with various scientific instruments and launch them. Such tools enable students to perform activities that they would not have access to in a regular classroom. Finally, examples of the tools allowing *hypotheses testing* are the control room and solution form. In the control room, students study the data coming back from probes to test their hypothesis and then write up their solution using the solution form.

Data Sources

To address the two research questions, we studied students' log files to see how students actually used the tools and then examined the tool use patterns of students in high and low performance groups based upon their scores of the solution to the problem.

Log files. All student actions performed while using Alien Rescue were logged to a data file. The log file consisted of time and date stamped entries for each student. The data set consisted of the number of times a student accessed each of the 13 cognitive tools and the amount of time the student stayed in each tool. A suggested lesson plan for each of the 15 days was provided in a teacher's manual. These lesson plans reflected the program designers' view on how Alien Rescue can best be implemented based upon its design principles.

Depending on the suggested primary task(s) that a student might perform during the entire process, the 15-day process to solve the central problem can be grouped into five stages. Stage 1 (Exploration) consists of days 1-2, during which students explore to get familiar with the environment and define the problem. Stage 2 (Research Phase I) consists of days 3-6, during which students conduct research and refine the problem. Stage 3 (Research Phase II) consists of days 7-9, when students continue to research and generate hypotheses. Stage 4 (Hypothesis Testing) consists of days 10-12, when students test their hypotheses and conduct further research. Finally, stage 5 (Solution Generation) consists of days 13-15, when students finalize their solution to the problem and write up their rationale. These five stages of problem-solving were not introduced to the students and the students had the freedom to determine how they wanted to use the tools to proceed. The log information was recorded for each day of use and grouped into these five stages.

Alien Rescue was in a pilot testing stage when this study took place. Computer crashes due to various technical problems resulted in some corrupted, lost, or incomplete log files. In this study, the log files of 60 students were used for this study. To ensure that the chosen log files were representative of the sample, the 60 cases were randomly selected for inclusion. They reflected a representation of 30 cases from each of the two teachers' classes. To be included in the analysis, the log data for each case must have been complete, reflecting all 15 days of use on each of the 13 tool variables. Incomplete log files were excluded. The final selection of the 60 cases mirrored the demographics of the sample but contained, purposefully, an equal number of male and female students.

Solution scores. Students' performance is measured by how well they solve the problem in Alien Rescue. Toward the end of using the program, students provide their solutions to the problem via an online solution form supplied in the program. Students must select, via the online form, a world to serve as a new home for each of the six species, as well as provide their rationale for why this world is a good choice. To encourage sixth graders to use their higher-order thinking skills, the software program was intentionally developed in such a way that there is more than one good choice for each alien species. Some choices of the worlds are better than others, and some have obvious drawbacks. Students must provide reasons for their choices. Such a design consideration departs from other educational programs in which there is only one correct answer to a problem. To help sixth graders in their thinking process, a cognitive tool is provided, expert modeling. The expert modeled the writing of a rationale for a new home he selected for one of the six species. The expert discussed the rationale for his choice and the drawbacks associated with it. Students could view the expert's solution form whenever they wanted. The classroom teachers used the expert's sample rationale to discuss how a solution form should be written.

Students' solutions for three species, not including the species the expert already modeled, were used in this study. A rubric, created and used in a previous study using Alien Rescue with a similar population (Pedersen & Liu, 2002), was adopted for this study. The solution for each species was first evaluated separately and then the scores for the three species were totaled. The evaluation of the solution focused on the following aspects: (a) if the choice for the new home is appropriate (students get more points if their selected world is a best choice, fewer points if the selection is an acceptable choice, and no points if their choice is a bad one); (b) if a topic sentence is provided in the solution form; (c) if supporting details are provided; (d) if potential drawback(s) are mentioned (as recognizing drawbacks is as important as selecting the appropriate choices); and finally (e) if the rationale is persuasive overall (see Table 2). Teachers discussed with the students the importance of including a topic sentence and providing details in writing the solution.

These grading criteria emphasized students' justification skills and reflected what was considered to be important to include in a solution form by the program designers and subject-matter experts. The expert's solution illustrated these criteria. According to Shin, Jonassen, and McGee (2003), "the process of justification requires the [problem] solvers to identify the various perspectives that impact the problem situation, provide supporting arguments and evidence about opposing perspectives, evaluate information, and develop and argue for a reasonable solution" (p. 7). Through the process of justifying their solutions, students practice their analyzing, synthesizing, and argumentation skills. For the three species, the score could range from 0 to 36.

Using the same method as in the previous study (Pedersen & Liu), two researchers scored 10% of the solution forms together using the rubric to ensure they applied the same criteria in scoring. Then the raters proceeded to score the remaining forms independently. Whenever there were questions during the entire grading process, the raters exchanged views to resolve any disagreement. The raters compared and discussed their final ratings until they reached an agreement of 100%.

----------Insert Table 2 here-------------

Procedure and Context

Students used Alien Rescue in their daily 45-minute science class for three weeks. Students worked in a computer lab equipped with Dell desktop computers with 386 processors. Each student had a computer for his or her use. Two experienced science teachers, though novice computer users, taught the sixth-grade classes. They participated in a two-day training workshop, during which the philosophy and different attributes of a student-centered learning environment like Alien Rescue and its PBL approach were discussed in depth. The two teachers did not do any direct teaching of what students were to do specifically. Their primary role is that of a facilitator. In day one, after watching the scenario presented by Alien Rescue, the teachers and the students held a discussion on what they primary task was. For the rest of 15-days, teachers let the students decide what their learning tasks were for each day and how to approach to solve the problem

Classroom observations revealed that each day teachers began the lesson with a mini-discussion on what the students did in the previous day and addressed any questions that came up. Students' questions were often answered by more questions from the teachers or answered by other students. Then the students worked on the computer. The teachers walked around the room answering students' questions, checking their progress, and ensuring students were on task. Most days, the lesson ended with another short discussion on what the students accomplished that day, any questions that surfaced, and what the goal should be for the next day. Because all the necessary tools for students to work on the problem were provided via technology in this PBL environment, it was possible for the teachers to spend most of the class time interacting with the students individually. The two teachers provided scaffolding to the students through daily questioning, answering, and discussion. The log files and solution scores were collected at the end of the study.

Analyses of Data

To answer the first research question " How are the built-in cognitive tools used in relation to the problem-solving process the sixth graders are engaged in?" we first performed descriptive analyses on the frequency of tool use for the entire 15-day time interval. We examined how each of the 13 tools was used. This analysis gave us an overall picture of tool use patterns.

We then examined whether particular patterns of tool use were associated with particular stages of problem-solving. We used cluster analysis to identify patterns of tool use (i.e. navigation profiles). Students' navigation through the environment is based entirely on how they use the tools. The frequency with which a student uses each of the 13 tools comprises their navigational profile. With cluster analysis, a data reduction technique, the navigational profiles of all 60 students are reduced to a few general profiles to account for the variation in frequency of navigational choices. Such profiles allowed us to identify general usage patterns of tool use. Literature has shown that cluster analysis is useful in identifying navigation profiles and often used when no a priori groups are known to exist (Barab, Bowdish, & Lawless, 1997; Lawless &

Kulikowich, 1996). By examining how students fell into natural groupings based upon how they used the tools, we could determine which tools were most frequently accessed and which tools were least frequently accessed at a particular stage. We could then infer whether the importance of different tools changed across subsequent problem-solving stages.

Five cluster analyses were conducted, one for each of the five stages. For each cluster analysis, the tool selections by each student were the 13 variables. These variables comprised the dependent vector of scores in a Ward's hierarchical cluster analysis, a procedure that can recover the underlying structure of the data effectively (Alexander, Jetton, & Kulikowich, 1995). All the variables were standardized prior to the analysis. Since the scale of measurement was identical across all variables, the method used to compute similarities in tool use was Rosenberg's profile dissimilarity distance (Davison, 1992; Rosenberg & Jones, 1972).

To determine the number of clusters to extract, we used the information presented in the agglomeration schedule to graph a scree-plot, a graph of the distance between the clusters by the number of clusters (Barab et al.). Greater distances between clusters indicate that dissimilar clusters are being merged. Smaller distances between clusters indicate relatively similar clusters are being merged. For each of the cluster analyses run at each of the five stages, we inspected the scree-plots to identify the point at which the distance between subsequent numbers of clusters decreased. This "elbow" in the graph (Stevens, 1997) indicates a cluster solution where the distance between subjects within clusters is minimized and the distance between clusters is maximized, in other words maximizing the similarity of subjects within clusters and minimizing the similarity between clusters. Using this method, six clusters were extracted at each stage.

To answer the second research question, “Are there any differences in tool use patterns for students in high and low performance groups?” we first grouped students into the top and bottom thirds using the mean solution score. We then examined the tool use by students in the top and bottom thirds at each of the five problem-solving stages. At each stage, a multivariate analysis of variance was performed with performance level (top third vs. bottom third) as the independent variable, and frequency of tool use in each of four tool categories at that stage as the dependent variables.

Results

Overall Tool Use Patterns

The analyses across the five stages revealed an overall pattern of tool use by the students. We converted raw frequencies of tool access to standard scores to enable us to compare tool use across all 13 tools. We report standard scores in Figures 3 and 4. At the *exploration* stage, tools such as the solar database, mission database, notebook, and probe builder were most often accessed. Other tools were also accessed. Students were apparently exploring various aspects of the environment, going from room to room as well as examining the various tools. At the *research I* stage, the use of the alien, solar, and mission databases was at their highest. The notebook was frequently used as well. These tools share cognitive load and support cognitive processing. These outcomes showed that students were searching, researching, and recording information. At the *research II* stage, while the previous tools were still used, patterns indicated that the students began to frequent the probe builder room, launcher room, and control room more often, indicating that they began to collect new data. At *hypothesis testing* and *solution generation* stages, the tool use concentrated mostly on those that support hypothesis generation and testing (see Table 3). That is, the students appeared to have selected tools relevant to the stages of the problem-solving process they were at.

Figure 3 contrasts the use of tools at the research I stage with the use of tools at the solution generation stage, providing a visual representation of tool use patterns at two different stages. Tools that support cognitive processing increase in access and peak at the earlier stage then decline while the tools that support hypothesis testing increase in access and peak at the last stage. Figure 4 provides a summary view of tool use in each of the four categories. Essentially, during the beginning and middle of the problem-solving process, students made the most use of tools that share cognitive load and support cognitive processing. During the middle and near the end of the problem-solving process, students made the most use of tools that support activities otherwise not possible or hypothesis testing. The figures provided a visual representation of tool use patterns.

----------------Insert Table 3 here-----------

----------------Insert Figures 3-4 here-------

Tool Use Patterns at Each of the Five Stages

Apart from the overall tool use patterns discussed above, the clusters identified at each of the five stages provided insight into how different types of tools available in Alien Rescue were used to solve the problem at different stages. For ease of interpretation we focused on those clusters that accounted for the largest number of students at each stage, rather than a detailed discussion on how each of the six clusters at each stage behaved.

At the *exploration* stage, students can best be characterized as exploring tools available in both layers of the interface. The patterns suggest that the students were exploring all five rooms of the virtual space station as well as the entire collection of tools contained in the retractable overlay. In particular, they appeared to have satisfied their curiosity by frequently accessing a few rooms or tools. For example, one cluster of students (n =16) most frequently accessed the notebook (M_{Freq}=36.33), another cluster of students (*n* =18) accessed the probe builder most (M_{Freq} =47.61), and a third cluster of students (*n* =14) accessed the solar system database most (M_{Freq} =45.43). The notebook is a tool that supports cognitive processing, the probe builder is a tool that allows students to test ideas within the problem-solving context, and the solar system database is a tool that supports cognitive load.

At the *research I* stage, students' free exploration of the environment appeared to have led either to a conceptualization of the problem or to a preoccupation with certain tools. For example, one cluster of students (*n* =22) most often accessed the solar system database tool (M_{Freq} =75.5). Another cluster of students (*n*=21) discovered how to coordinate access to multiple tools within the same layer of the interface, namely the solar system database (M_{Freq} =115.63), with the electronic notebook (M_{Freq} =78). However, a minority of the students (*n*=5) became preoccupied with a subset of tools such as the probe builder (M_{Freq} =268) and control room (M_{Freq} =100.5). The probe builder and control room are simulation tools that provide the most entertainment value for the students and students consider them most fun to use. These tools are primarily used to interpret, organize, collect new data, and build a rationale; and are most useful during middle and later problem-solving stages. Given the early stage of problem-solving process these students were in, such tool use indicated that these students accessed the least productive tools.

The majority students at the *research II* stage accessed tools that share cognitive load in connection with the tools that support cognitive processing, or tools that share cognitive load in connection with tools that support hypothesis testing. For example, one cluster of students (*n* =11) most frequently accessed the solar system database (M_{Freq} =59.22) in connection with the notebook (M_{Freq} =69.82). Another cluster of students (*n* =23) frequented the solar system database (*M*=73.52) and the probe builder most (M_{Freq} =61.26).

At the *hypothesis testing* stage, the majority of students continued to frequently access multiple tools within both layers of the interface. One cluster of students (*n* =17) frequently accessed the probe builder (M_{Freq} =255) and control room (M_{Freq} =68.65). The control room is a tool that supports hypothesis testing. Another cluster of students (*n* =12) frequently accessed the mission database (M_{Freq} =34.25), solar system database (M_{Freq} =95.25), probe builder (M_{Freq} =83.83), and control room (M_{Freq} =35.67). The mission database is a tool that supports cognitive load. A third cluster of students (*n*=18) frequently accessed the notebook (M_{Freq} =48.94), solar system database (M_{Freq} =57.11), probe builder (M_{Freq} =108.78), and control room (M_{Freq} =84.72).

The patterns of tool use at the final stage (*solution generation*) indicated that most students were focusing primarily on the tools used to interpret data, organize data, collect new data, and build a rationale. The cluster with the largest number of students (*n* =39) most frequently accessed the probe builder (M_{Freq} =107.56) in connection with the control room (M_{Freq} =105.59). Apparently students were integrating information and finalizing their solution at this stage.

Tool Use Patterns and Performance

Students' performance is measured by their solution to the problem: the worlds they selected as new homes for each alien species and the rationale they provided. We divided the solution scores of all students into top and bottom thirds based upon their mean solution score (*M*= 16.55) and examined how students in the top third (*M*=24.56, *n*=9) and bottom third (*M*=8.77, *n*=13) used the tools. The solution scores ranged 0 to 36. A *t*-test indicated that the top and bottom thirds of the solution scores were significantly different from each other (*t*=4.13,

p<.01). We then investigated how the students in the top and bottom thirds used the tools at each of the 5 stages. Five MANOVAs were performed, one for each stage, with student performance level (top and bottom thirds) as the independent variable and frequency of tool use in each of the four tool categories as the dependent variables.

At the first four stages (*exploration*, *research I*, *research II*, and *hypothesis testing*), there were no statistically significant differences. However, a descriptive analysis of the data indicated that the students in the top third exhibited clearly different tool use patterns than those by the students in the bottom third. At the *exploration* stage, there was a difference in accessing the number of tools supporting cognitive processing by the top third (M =53.56) and bottom third (M =28.69) of students. Students in the top third used such cognitive processing tools as the notebook and bookmark more. At the *hypothesis testing* stage, the top third students used more tools than the bottom third in all four categories. For tools supporting cognitive processing, students in the top third used an average of 50.78 times while students in the bottom third used an average of 28.69 times. For tools sharing cognitive load, students in the top third used an average of 74.00 times while students in the bottom third used an average of 63.69. For tools supporting activities out of reach otherwise, the top third accessed an average of 182.33 times while the bottom third accessed an average of 171.69 times. For tools supporting hypothesis testing, the top third accessed an average of 179.11 times while the bottom third accessed an average of 126.69 times.

The analysis of tool use at the last stage (*solution generation*) yielded a significant multivariate result ($F(4, 17)$=4.406, p<.05). Univariate ANOVAs were then performed for each of the dependent variables. Differences in two categories of tool use contributed to this overall significance: cognitive processing ($F(1, 20)$=5.348, p<.05) and cognitive load ($F(1, 20)$=4.784, *p*<.05). Students in the top third accessed both categories of tools significantly less (*M* =9.56 for cognitive processing tools; *M* =8.44 for cognitive load tools) than the students in the bottom third (*M* =25.23 for cognitive processing tools; *M* =36.85 for cognitive load tools).

Discussion

The findings of this study provided empirical evidence to show that certain cognitive tools are used at certain problem-solving stages by these sixth graders. Specifically, early in the problem-solving process the tools which support cognitive processing and share cognitive load play a central role in conceptualizing the problem as students search, locate and select relevant information, and research. Once the students have conceptualized the problem, their reliance on tools that share cognitive load and support cognitive processing fades while their reliance on tools that support activities otherwise not possible and hypothesis testing grows. At this point, the tools that support cognitive processing and share cognitive load necessarily play a less central role and are used more for reference in conjunction with the tasks of collecting new data, interpreting data, organizing data, and building a rationale.

The shift in tool use from stage to stage provides a glimpse of how the sixth-graders are progressing in their problem-solving process. The results indicated that the majority of the students were using the tools appropriate for various stages, while a few students remained preoccupied with a set of tools (i.e. simulation tools) that offered the highest entertainment value. Although the findings on tool use patterns and students' performance are inconclusive, they do show that students in the top third of their performance level made more appropriate use of the tools than the students at the bottom third. The students in the top third used cognitive processing tools more at the *exploration* stage. They used a number of tools (such as concepts database, mission database, notebook, bookmark, control room, solution form) much more than the bottom third of students at the *hypothesis testing* stage. The active use of these relevant tools at these stages is an indication of a higher degree of engagement in solving the problem by the top third students. On the contrary, the bottom third of the students used tools of cognitive processing and cognitive load significantly more at the final stage. These two categories of tools should be of more relevance to the earlier stages of problem-solving. Together, the patterns of tool use by the top and bottom thirds suggest that the students in the top third began to use tools to conceptualize the problem earlier than the students in the bottom third and they used tools more relevant to the stages of problem-solving they were at. The students in the top third appeared to have made more productive use of tools than the students in the bottom third.

Since each of the 13 tools performs a specific function and is needed at different times during the entire problem-solving process, it is not surprising that the students selected the tools relevant to their stages. However, using tools appropriately due to the nature of the given tasks may not always be the case. Oliver and Hannafin (2000) examined how middle school students used cognitive tools to help them collect, organize, annotate, and evaluate complex information. They found the tools mostly supported lower-level information gathering and thinking rather than higher-order reasoning for which the tools were designed. The students failed to use the tools to the full potential. If students are not aware of how and why they should use tools provided to them, then the tools will not be effective at providing the guidance for which they are intended. In this study, most sixth graders appeared to recognize when to use certain tools and were able to use these tools to solve the central problem. As part of the total solution scores, the students must select a home for the aliens. The data showed that 82% of the students achieved this goal.

In addition to using the appropriate tools for problem-solving, coordinating different categories of tools is another important way the tools can scaffold students' thinking. The simultaneous and unobtrusive availability of 13 tools is accomplished through a two-layered interface design. Tools such as databases, notebook, expert-modeling (layer 1 tools), are most applicable during the beginning and middle stages of problem-solving. Yet these tools remain immediately accessible to a student throughout the process. Tools such as probe builder, probe launcher, control room, and solution form (layer 2 tools) are most relevant during the middle and late stages of the problem-solving process. Students access them when they actually navigate to a room. By design, the two-layered interface encourages the use of multiple tools and allows productive comparisons of information (see Figures 1-2).

The increasing use of multiple tools from early stages to later stages in problem-solving is an indication that the sixth-graders not only became comfortable in using the tools, but also realized how different tools can be used together to solve the problem. The tools, though relevant to different problem-solving stages, are not presented in any hierarchical order. The selection of tools is the students' decision. Becoming acquainted with the nature, function, and timing of all 13 tools could prove overwhelming to sixth-graders. Yet, such a design creates an opportunity in which students must continuously exercise their decision-making and evaluation skills to see which tools to use, when, and why. By providing tools both stage appropriate and complementary, the program makes a reservoir of information manageable, and places potential connections within the student's grasp. This allows students to create the conditions for their own learning.

The tool use patterns suggested that the built-in cognitive tools assisted the students' understanding of the problem and facilitated their strategic problem-solving. Using cognitive tools to externalize problems can, and often does, mediate a learner's conception of a problem (Jonassen, 2003). External representations can guide conceptualization and interpretation of a problem (Zhang, 1997; Zhang & Norman, 1994). They can also “constrain the range of possible cognitive behaviors in the sense that some behaviors are allowed and others prohibited” (Zhang, 1997, p. 3). An example to support this theory is found in a closer examination of how the alien database and solar system database are used. These two tools are essential data sources for solving the problem. Students are expected to use them hand in hand. The data showed that the students stayed in the alien database for 2.02 minutes every time they accessed it ($Total_{Freq}$= 2444; $Total_{Time}$=4932; Ratio=2.02), whereas they stayed in the solar database for .42 minute every time they accessed it ($Total_{Freq}$= 14476; $Total_{Time}$=6104; Ratio=0.42) (see Table 3). Interestingly, however, students accessed the solar database almost six times more frequently. An explanation for this finding lies in the way the two databases are designed. The alien database (i.e. research room) is a layer 1 tool available only when the students go into it, and the solar database is a layer 2 tool available at any time. Apparently the design of the two tools constrained how the tools are used. That is, the results suggest that the students go to the alien database first. While they are in the alien database, looking up the various attributes of a species, they would click to open the solar system database to search for relevant planets for a possible new home for that species. The brief, but frequent, visits to the solar system database suggest that students go there to find specific information while staying in the alien database researching the species (Figure 2b). If the design of the two databases was reversed, we would expect the access patterns to be reversed as well.

Scaffolding students' learning with Alien Rescue can come from teachers as well as the tools. Because the two teachers did not do any direct teaching (see *Procedure and Context* section), and the use of the program comprised about 80% of the class time in this study, it is reasonable to assume much of the scaffolding came from students interacting with the tools provided in the environment. Using the tools in various categories over the entire problem-solving process, students are provided an opportunity to apply such higher-level thinking skills as focusing, researching, organizing, analyzing, generating, integrating, and evaluating.

The benefits of cognitive tools to support learners' cognitive processes have been recognized. However, there is little empirical research to substantiate this notion. This study examined the actual tool use patterns and how tool uses are associated with different problem-solving stages. A limitation of this study is that we used the log data to examine students' actual use of tools. Although the log data provided an objective and unobtrusive way for investigation, we can only infer about the thinking processes students were engaged in while selecting the tools. A subsequent study has therefore been conducted to investigate explicitly the connection between students' tool use and their cognitive processes (Liu, Bera, Corliss, Svinicki, & Beth, 2004). Given problem-solving in PBL is often a collaborative process as it is in Alien Rescue, a related study is performed to understand how groups access cognitive tools and in what ways the group patterns of tool use may affect students' individual performance (Bera & Liu, in press). Given the finding of different tool use patterns by students in the high and low performance groups, another study will be conducted to understand how experts use the tools to assist their problem-solving as compared to the novice sixth-graders. Continuous research on the topic will further enhance our understanding of the role cognitive tools can play in scaffolding learners' problem-solving and how to build effective technology support into a PBL environment.

References

Alexander, P. A., Jetton, T. L., & Kulikowich, J. M. (1995). Interrelationship of knowledge, interest, and recall: Assessing a model of domain learning. *Journal of Educational Psychology*, *87*(4), 559-575.

Barab, S. A., Bowdish, B. E. & Lawless, K. (1997). Hypermedia navigation: Profiles of hypermedia users. *Educational Technology Research and Development*, *45* (3), 23-41.

Bera, S. & Liu, M. (in press). Cognitive Tools, Individual Differences, and Group Processing as Mediating Factors in a Hypermedia Environment. *Computers in Human Behavior*.

Bransford, J., Brown, A. L., and Cocking, R. R. (Eds.) (2000). *How people learn: Brain, mind, experience, and school: Expanded Edition*. Washington, DC: National Academy Press.

Davison, M. L. (1992). *Multidimensional scaling*. Malabar, FL: Krieger Publishing Company.

Hawkins, J. and Pea, R. D. (1987). Tools for bridging the cultures of everyday and scientific thinking. *Journal of Research in Science Teaching, 24*(4), 291-307.

Iiyoshi, T. and Hannafin, M. (2002). Cognitive Tools and User-Centered Learning Environments: Rethinking Tools, Functions, and Applications. *Proceedings of the World Conference on Educational Multimedia & Hypermedia 2002*, (pp. 831-836).

Jonassen, D. H. (1996). *Computers in the classroom: Mindtools for critical thinking*. Englewood Cliffs, NJ: Prentice Hall, Inc.

Jonassen, D. H. (2003). Using Cognitive Tools to Represent Problems. *Journal of Research on Technology in Education, 35*(3), 362-381.

Jonassen D. H., and Reeves, T. C. (1996). Learning with technology: Using computers as cognitive tools. In D. H. Jonassen (Ed.), *Handbook of research for educational communications and technology* (pp. 693-719). NY: Macmillan.

Kozma, R. B. (1987). The implications of cognitive psychology for computer-based learning tools. *Educational Technology, 27* (11), 20-25.

Lajoie, S. P. (1993). Computer environments as cognitive tools for enhancing learning. In S. P. Lajoie and S. J. Derry (Eds.), *Computers as cognitive tools* (pp.261-288). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Lawless, K. A., & Kulikowich, J. M. (1996). Understanding hypertext navigation through cluster analysis. *Journal of Educational Computing Research*, *14*(4), 385-399.

Liu, M, Williams, D., & Pedersen, S. (2002). Alien Rescue: A Problem-Based Hypermedia Learning Environment for Middle School Science. *Journal of Educational Technology Systems, 30*(3), 255-270.

Liu, M., Bera, S., Corliss, S., Svinicki, M., & Beth, A. (Submitted March, 2004). Understanding the Connection Between Cognitive Tool Use and Cognitive Processes as used by Sixth Graders in a Problem-Based Hypermedia Learning Environment. *Journal of Educational Computing Research*.

Pea, R. D. (1985). Beyond amplification: Using the computer to reorganize mental functioning. *Educational Psychologist, 20*, 167-182.

Pedersen, S., and Liu, M. (2002). The effects of modeling expert cognitive strategies during problem-based learning. *Journal of Educational Computing Research*. *26*(4), 353-380.

Rosenberg, S. & Jones, R. (1972). A method of investigating and representing a person's implicit theory of personality: Theodore Dreiser's view of people. *Journal of Personality and Social Psychology, 22*, 372-386.

Salomon, G., Perkins, D. N. & Globerson, T. (1991). Partners in cognition: Extending human intelligent technologies. *Educational Researcher , 20*, 2-9.

Savery, J.R. and Duffy, T.M. (1995) Problem-based learning: An instructional model and its constructivist framework, *Educational Technology, 35,* 31-38.

Shin, N., Jonassen, D., & McGee, S. (2003). Predictors of well-structured and ill-structured problem-solving in an astronomy simulation. *Journal of Research in Science Teaching*, 40(1), 6-33.

Stevens, J. (1997). *Applied multivariate statistics for the social sciences* (3rd ed.). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Sweller, J. & Chandler, P. (1994). Why some material is difficult to learn. *Cognition and Instruction*, *12*(3), 185-233.

Zhang, J. (1997). The nature of external representation in problem-solving. *Cognitive Science*, *21*, 179-217.

Zhang, J. & Norman, D. A. (1994). Representations in distributed cognitive tasks. *Cognitive Science*, *18*, 87-122.