Students' Problem Solving as Mediated by Their Cognitive Tool Use: A Study of Tool Use Patterns[1]

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Abstract

The purpose of this study was to use multiple data sources, both objective and subjective, to capture students' thinking processes as they were engaged in problem-solving, examine the cognitive tool use patterns, and understand what tools were used and why they were used. The findings of this study confirmed previous research and provided clear empirical evidence supporting the theoretical notion that technology-based cognitive tools play an important role in assisting students' problem-solving. Students' tool use patterns were discussed in the context of their problem solving.

(Keywords: cognitive tools, cognitive processes, tool use pattern, technology, problem solving)

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Introduction

The potential of technology-based cognitive tools to extend human thinking has been continuously explored (Iiyoshi, Hannafin, & Wang, 2005; Kim & Reeves, 2007; Lajoie, 1993, 2000). We are interested in learning how computer-based cognitive tools can assist in problem solving and seek to provide some empirical evidence to support the notion that technology-based cognitive tools play an important role in assisting students' problem solving and learning (Jonassen & Reeves, 1996). In our previous research, we used log data (computer generated audit trail) to examine students' tool use patterns across various stages of problem solving as they interacted with a problem solving environment (Liu & Bera, 2005). The results showed that the use of different types of tools was associated with different stages of problem solving and found that the students increasingly used multiple tools in the later stages of their problem solving process. In another study, we further investigated the connection between students' tool use and their cognitive processes, as exhibited in self-reported data, and found that different types of cognitive tools were used for different types of cognitive processes; a connection was established between cognitive tool use and cognitive processes (Liu, Bera, Corliss, Svinicki, & Beth, 2004).

The log data provided an objective and unobtrusive way to examine students' actual use of tools, and students' self-reported data allowed us to infer students' thinking processes as they selected various tools. As a follow-up step in our investigation, we intend to match log data with self-reported surveys to more explicitly investigate students' thinking processes as reflected by their tool use. In addition, we added stimulated recall as a way to elicit evidence of students' cognitive processes at specific times. Our goal in this study was to further examine cognitive tool use patterns as students were engaged in problem solving processes by using multiple data sources and to investigate whether students with high and low performance scores used cognitive tools similarly.

Research Framework

Cognitive tools are instruments that can enhance the cognitive powers of learners during their thinking, problem solving, and learning (Jonassen & Reeves, 1996; Pea, 1985; Salomon, Perkins, & Globerson, 1991). According to Lajoie (1993), computer learning tools can be categorized into four types according to the functions they serve: (a) support cognitive and metacognitive processes; (b) share cognitive load by providing support for lower level cognitive skills so that resources are left for higher order thinking skills; (c) allow learners to engage in cognitive activities that would be out of their reach otherwise; and (d) allow learners to generate and test hypotheses in the context of problem solving.

Cognitive tools are of particular importance in a problem-solving situation in that they can assist students in developing problem-solving skills (Jonassen & Reeves, 1996; Kozma, 1987; Pea, 1985; Salomon, Perkins, & Globerson, 1991). Problem solving is cognitive processing aimed at accomplishing certain goals when the solution is unknown (Mayer & Wittrock, 1996). Literature indicates that learners typically have difficulty managing complex problem solving tasks (Hawkins & Pea, 1987) such as problem representation. In any problem-solving situation, both internal and external representations are evoked (Zhang & Norman, 1994). Internal representations of problems are mediated through schema, propositions, and mental images, while external representations exist outside the mind, often in the form of physical symbols or external rules (Zhang, 1990). A major difficulty that many learners encounter when problem solving is in forming external representations of internal knowledge (Jonassen, 2003). When learners can rely on external representations of problems, they are afforded substantial benefits. External representations can anchor and structure cognitive behaviors, serve as memory aids, and provide access to information that can be quickly perceived and used (Zhang, 1990; 1997; Zhang & Norman, 1994). However, novices generally lack the mental models necessary for constructing external representations of problems. The use of cognitive tools can remove this burden by helping learners externalize and conceptualize problems (Jonassen, 2003) which can help them perceive relationships among concepts and attributes (Zhang, 1997; Zhang & Norman, 1994). As a form of external representation, the design of cognitive tools can allow the internal and external representations of a problem to productively interact and facilitate learners' processing of the problem (Jonassen, 2000; Sweller & Chandler, 1994).

Literature has documented several notable learning environments where cognitive tools have been implemented to facilitate learning. For example, *Exploring the Nardoo*, a multimedia environment for studying a river ecosystem, provides a personal digital assistant, nine genre templates, and three simulators. These tools assist learners in generating hypotheses, communicating, and preparing multimedia reports (Harper, Hedberg, Corderoy, & Wright, 2000). In the *Web-based Inquiry Science Environment (WISE),* an inquiry map and a notebook tool are provided along with metacognitive prompts to scaffold students' inquiry (Linn, Clark, & Slotta, 2003). In Bio-World (Lajoie, 1993), a simulation for medical informatics, tools are provided that enable students to select evidence from patient medical history, conduct research in a medical library, hypothesize a diagnosis, perform diagnostic tests, and make final arguments based on evidence.

However, building cognitive tools into an environment does not ensure that learners will use them when they are needed or for their intended purposes. In their investigation of middle school students' use of cognitive tools for a scientific inquiry, Oliver and Hannafin (2000) found that the tools mostly supported lower-level information gathering and thinking rather than facilitating the higher-order reasoning for which they were designed. Their study revealed that tools may not be effective at providing guidance if the students are not aware of when and how they should use them.

After reviewing literature on computer-based cognitive tools, Iiyoshi and his colleagues proposed several areas for further investigation that may inform the design and implementation of tools in learning environments. They recommend inquiry into the facilitation of tool use and the affordances of domain-free versus domain-specific tools, and examination of the nature, patterns, and products of tool use (Iiyoshi, Hannafin, & Wang, 2005). In discussing the patterns of tool use, they stated, "we understand comparatively little about how tools are actually used by students, yet we continue to develop and refine specific features and make assumptions about their use and utility" (p. 292). Therefore, understanding how tools are actually used and studying tool use patterns should help us design more effective tools and ensure tools are used as intended.

Goal of This Study

This research built upon two previous studies on understanding tool use patterns (Liu & Bera, 2005; Liu et al, 2004). The goal was to further investigate the connection between cognitive tool use and processes involved in solving a complex problem. We asked the following research questions:

1. What cognitive tool use patterns emerge as college students engage in problem-solving processes? Why?

2. Do college students with high and low performance scores use the cognitive tools in a similar way?

To address research question one, we examined 1) activity log files to determine the overall tool use patterns; 2) students' self-reported survey data to understand which cognitive tools were used for various cognitive processes, and 3) stimulated recall interview data to understand why students used a particular tool at a particular time. Our intention was to use multiple data sources, both objective and subjective, to capture students' thinking processes and understand which tools were used and why. To answer the second research question, we looked at the diversity, consistency, and activeness of tool use, as used in Liu, Bera, Corliss, Svinicki, & Beth (2004), by high and low performance groups.

The context for our investigation in this study was the same problem-solving environment used in the previous research, a hypermedia problem-based learning environment in space science designed for sixth graders (see description below). In order to get learners to describe their thinking process explicitly and in detail, we chose to use college undergraduates instead of sixth graders in this study. Our previous experience showed that it was very difficult for sixth graders to articulate their thought processes, and we felt that college students would be able to more clearly describe what they were thinking during different problem-solving steps.

Method

Sample

Participants for this study consisted of 61 undergraduate students enrolled in education courses at a large public university in the southwestern United States. These students were part of a subject pool and agreed to participate in the study in order to fulfill course requirements.

Problem-Solving Context

Alien Rescue (Liu, Williams, & Pedersen, 2002), a hypermedia program, presents a situated problem-solving context in which students are prompted to identify suitable homes within the solar system for six characteristically different alien species that have been displaced from their home planets. Each alien species possesses specific requirements that the students, in the role of scientists aboard a space station, must consider as they research and ultimately identify the most appropriate relocation site(s). A critical aspect of the program design lies in the fact that there are no definitive outcomes and some planets are more suitable than others. Students are charged with presenting both an appropriate choice as well as a justification.

Problem-solving activities within *Alien Rescue* closely mirror those that might be followed by research scientists engaged in the processes of scientific inquiry. Research is a central theme as learners identify the characteristics and requirements of each alien species, explore locations throughout the solar system to identify potential solution candidates, test and validate their hypotheses, and generate a solution. To this end, 13 cognitive tools with various functions exist within the virtual environment and support a range of tasks related to successfully generating a solution. By applying Lajoie's (1993) four conceptual categories, the tools may be categorized in terms of their primary function: Tools (a) share cognitive load, (b) support cognitive processes, (c) support cognitive activities that would otherwise be out of reach, and (d) support hypothesis generation and testing.

In order to *share cognitive load,* for example, the four database features (i.e. alien database, solar system database, mission database, concept database) provide access to highly organized information stores that contain textual, visual, and animated media. These databases are essential because they provide information useful to begin the problem-solving process.

Additionally, these tools can help learners manage their cognitive load by reducing the memory burden and by implementing useful knowledge structures in the way the information is stored and accessed via the program interface. As an example, a student wishing to obtain information on the Akona alien species could access the alien database and receive data on the alien's appearance, habitat, diet, and behavior.

The bookmark feature, notebook, and expert tool are all examples of tools that s*upport cognitive processes*. The key characteristic of these tools is that they serve to augment the learners' existing problem-solving capabilities. The video-based expert, for example, can be accessed by the learner should they encounter a particularly challenging stage in their problem-solving activities in order to provide guidance and model behaviors that may lead to a solution. Likewise, the bookmark feature and notebook both assist the learner in organizing, storing, and retrieving information that can be used throughout the problem-solving processes.

Despite the information-richness of the database tools, the information they contain is not sufficient enough that the learners could completely justify a solution through their use alone. Two tools – the probe builder and probe launcher – are provided to *support cognitive activities that would be out of reach otherwise.* These tools support a very specific purpose within *Alien Rescue* by allowing the collection of additional data that are unavailable anywhere else within the program. Using the probe builder and probe launcher, learners are able to equip exploratory space probes with numerous measurement instruments such as thermometers, seismographs, and cameras; and then direct the probes to collect data on specific worlds of interest.

The control room and solution form both *allow hypothesis testing.* The control room provides an interface for the learners to observe data that the probes have captured and the solution form simply provides a space for the learners to generate and submit their completed solutions. Figure 1 provides screenshots of some of these tools. A detailed description of each tool under each category can be found in Liu et al. (2004), and more information about the program can be found at http://alienrescue.edb.utexas.edu/.

-------------------Insert Figure 1 Here -----------------

Data Sources

Alien Rescue is designed for fifteen 45-minute class sessions. When 6^{th} graders use it as part of their science curriculum (see Liu & Bera, 2005, Liu et al. 2004), teachers typically decide how many species their students will help find homes depending on the students' levels and curriculum goals of using it. Considering the age difference between sixth graders (the target audience of *Alien Rescue*) and college students, in this laboratory-like research setting and for the purpose of comparison all college participants were asked to find a home for one of the six species, the Akona, and were given 90-minutes to solve the problem.

There were four data sources in this study.

Log files. All student actions performed while using the program 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 used each tool. The participants were introduced to the research, watched a video-based problem scenario together, and were given a few minutes to orient themselves with the environment. Then, each participant was given 90 minutes to find a home for the Akona species. The log file represented the tools a student used and the amount of time he used each tool for the duration of 90 minutes.

Cognitive Task Questionnaire. The self-report *Cognitive Task Questionnaire* was created and first used in the study by Liu et al. (2004). It consisted of 20 cognitive processes identified using a task analysis. These 20 processes represent the key cognitive processes involved in problem solving with *Alien Rescue* and are grouped into four conceptual categories by two experts in human cognition who were familiar with problem solving in *Alien Rescue*: (a) understanding the problem, (b) identifying, gathering, and organizing information, (c) integrating information, and (d) evaluating the process and outcome. For example, one item says, "When using Alien Rescue, I first thought about the problem I needed to solve and figured out what I needed to do." Another item states, "When designing probes, I first decided what I wanted to find out and then chose instruments that would help me get that information." For each of the 20 statements, students first were asked to rate, using a Likert scale, the extent to which they engaged in each cognitive process, with 1 representing "not at all" and 5 representing "all the time." The higher the number, the more involved the student indicated she was in a particular cognitive process. Students were then asked to indicate which of the 13 tools they used while performing each of 20 cognitive activities to understand the connection between students' cognitive processes and their use of cognitive tools. They were asked to mark all the tools they used for each activity. (See Appendix A for the formatting of the questionnaire.)

Stimulated recall. Eleven participants volunteered to participate in stimulated recall interviews about their experience using *Alien Rescue*. Each of these eleven students was observed by a researcher as he/she worked through *Alien Rescue*. The researcher made notes of students' actions within the program. Upon completion of the program, individual interviews were conducted with these students and they were asked to describe what they were doing and thinking during key points in the problem-solving process. The interview lasted approximately 15 minutes for each student. Sample interview questions included:

"I noticed the first thing you did was go to the alien database and read about the alien species. Can you tell me why you did that and what you were thinking at that time?"

"I noticed you took notes while you read through the solar system database. Can you tell me what you were thinking at that time, and what type of things you were including in your notes?," and "Why did you click on the expert tool while you were designing probes?"

The interviews were audio recorded and transcribed for further analysis.

Performance scores. Students' performance was determined by how well they solved the problem. Although there are six alien species in the program, for the purpose of this study, all participants were asked to identify a solution for the same alien species: the Akona.

Complex problems are often ill-structured and contain multiple solutions and solution paths and sometimes no solution at all (Jonassen, 2003). Successful problem solving in such contexts is usually measured by how well problem solvers form their own interpretations and judgments about the problem, conceive appropriate courses of action, predict outcomes, test assumptions, and develop and argue for a solution. Therefore, the assessment of students' performance in *Alien Rescue* is not restricted to identification of a suitable home, but also considers the degree to which students justify and argue for the home they select based upon the evidence they have collected. According to Shin, Jonassen, and McGee (2003), "the process of justification requires 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).

In order to elicit these types of cognitive processes, *Alien Rescue* requires students to compose a recommendation that advocates the suitability of the home they select. An eight-point scale, based upon a version used in a previous study (Bera, 2004), was developed to score students' written responses. Evaluation of the students' recommendations focused on how well they analyzed and synthesized data to support their solution and advance an argument for the home they selected. Scores were determined by two key criteria: 1) The feasibility of homes they selected (certain home(s) are good while other(s) are poor choices given the characteristics of the alien species and the planets), and 2) The number of reasons they used to substantiate their choice. Students who recommended an uninhabitable planet were given a score of 1. A score of 2 was granted to students who recommended a feasible home and provided one reason to support their choice. An additional point was awarded for each reason students provided that was informed by the data analysis they conducted while working in *Alien Rescue*. For example, students who provided two reasons for their choice received a 3; students who provided three reasons received a 4, and so forth. The maximum score of 8 was awarded to students whose recommendations provided six or more reasons and presented limitations of the proposed home or gave consideration to how its constraints might be overcome.

Two researchers scored 10 percent of the recommendation forms together using the scale described above to ensure that they applied the same criteria during scoring. The researchers went through the entire scoring process of getting 100% inter-rater reliability. They then scored the remainder of the recommendation forms independently.

Procedure

Participants signed up to attend a research session that lasted approximately two hours in a campus computer lab. During the research session, each student had his or her own computer for use. At the beginning of the session, students were given a 10-minute introduction to the program. They were instructed how to log into the program, and briefly shown how to navigate through the program. Students watched the opening video scenario together. They were then given a few minutes to explore the environment and get familiar with the tools. Aside from an introductory explanation of each of the thirteen tools, the students were provided with no explicit guidance in terms of the sequence and proper use of each tool. Rather, *Alien Rescue* encourages the learners to freely establish and implement their own course of action. An essential goal of the program is that learners will engage in planning and decision-making in determining the best use of the affordances that *Alien Rescue* provides in order to arrive at the most optimal solution.

The participants were given 1 1/2 hours to work through the challenge. After 90-minutes, students were asked to submit the recommendation form where they listed the world they had chosen for the alien species and provided reasons to support their choice. Fifty participants then completed the *Cognitive Task Questionnaire* and 11 students participated in the stimulated recall interviews. The log data of all students were saved. Data of two students were dropped from the analyses because they did not complete the questionnaires. The final analyses represented data from 48 students who completed the *Cognitive Task Questionnaire* and 11 students who completed stimulated recall. The log files for these 59 students were used.

Results

Cognitive Tool Use Patterns

To answer our first research question, "What cognitive tool use patterns emerge as college students engaged in the problem-solving process?" we examined 1) tool use as shown in the log data, 2) self-reported tool use as indicated by the *Cognitive Task Questionnaire* and 3) participants' responses during stimulated recall interviews.

Tool use patterns as shown in log data. We analyzed log data to determine the frequency and duration of each tool used by the participants. The descriptive analysis indicated that all 13 tools were used. Tools such as the alien database, solar system database, mission database, notebook, probe builder, probe launcher, and control room were accessed more often than the other tools (see Table 1, highlighted with bold-face), and students used tools such as the alien database, solar system database, notebook, probe builder, and control room for longer periods of time. As described above, tools such as the alien and solar system databases contain critical content information for understanding the needs and characteristics of aliens and along with the attributes of locations within our solar system. These tools are essential in allowing students to understand the problem. To process the information, students relied on the notebook to take notes and later used the information to generate a solution. The probe builder and probe launcher support students in gathering additional data that the built-in databases do not provide. The control room allows students to interpret data sent back from the launched probes. Given the design of the cognitive tools, it is possible for students to access more than one tool at the same time (see Figure 1). Figure 2 shows the concurrent tool usage over the 90 minutes and further reveals higher use of tools sharing cognitive load at the beginning of the problem-solving process and the use of tools in this category continued throughout. Figure 2 also shows the relatively high uses of tools supporting cognitive processes overall and most importantly, the integrative use of all four categories of tool use (Lajoie, 1993) throughout the entire problem solving process. It seemed that students went back to access tools sharing cognitive load again toward the end of their problem solving.

-------------------Insert Table 1 Here -----------------

-------------------Insert Figure 2 Here -----------------

Tool use as shown in self-reported data. We then examined the participants' responses on the *Cognitive Task Questionnaire* to find potential relationships between tool use and student-reported cognitive processes. Chi Square analysis was performed between the frequencies of the four cognitive tool use categories (Lajoie, 1993) and the four cognitive process categories (as described above). Results showed a significant chi-square value (X^2 = 114.43, df=9, p < .01), indicating significant association between the four categories of tools and the four categories of cognitive processes (see Table 2). Inspection of the observed minus expected values indicates that three sets of relationships most likely contributed to this significant result:

1. Stronger associations between "tools that support cognitive processes" and two of the four cognitive process categories. Students reported higher than expected frequency of tool use in this tool category for "understanding the problem," and lower than expected frequency of tool use when "identifying, gathering, and organizing important information."
2. Stronger associations between "tools that support activities otherwise not possible" and three of the four cognitive process categories. Students reported higher than expected frequency of tool use in this tool category for "identifying, gathering, and organizing." Students reported lower than expected frequency of tool use in this tool category for the "understanding" and "evaluating" cognitive processes.
3. Stronger associations between "tools that support hypothesis testing" and one of the four cognitive process categories. Students reported higher than expected frequency of tool use in this tool category for the "integrating" cognitive process.

-------------------Insert Table 2 Here -----------------

Stimulated recall responses. Finally, we conducted stimulated recall interviews of 11 participants to understand why they chose to use certain tools at certain times. We observed these students as they worked through the program and then asked them questions about their problem-solving processes. Students' responses were analyzed following the "open coding" procedure as outlined in Strauss' and Corbin's (1998) grounded theory approach, where categories are thought to emerge from the data rather than through a priori prescription by the researchers. We abstracted themes from the data and compared these themes across student responses to determine when and why students used particular tools while solving the problem.

A pattern of tool use emerged from these interviews. During the first stage of the problem-solving process in *Alien Rescue* -- understanding the problem -- students reported using tools such as the *alien database, notebook*, and *expert*. On average, the alien database was the first tool used by the students. They reported using this tool to get an overview of the problem and to find information about the alien species. One student said, "I started out by finding out more about the species…finding out what the Akona are like." Some of the students reported using the notebook and the expert along with the alien database. One student reported, "I used the notebook so I wouldn't have to refer back…I was able to jot down information about the species that I could use for further investigation", and another mentioned that, "you could push that button (expert) to know what you should do." The notebook was used to record important information about the aliens, and the expert was used to determine if students felt they needed additional help (see Liu et al., 2004, for a detailed description of the tools).

As students moved to the second stage of problem solving -- identifying, gathering, and organizing important information -- they reported using the tools such as the spectrogram, solar system database, missions database, probe design room, probe launch room, expert, and notebook. These tools were used to learn more information about the needs of the alien species and the characteristics of the planets and moons of our solar system. For example, when asked about their use of these tools, students commented:

> “I wanted to get some information about the different planets and moons to see…what would correlate to the information about the species (solar system database).”
>
> “I wanted to see what other probes had found out in their own missions…(missions database).”
>
> ”The seismic activity was not in the database and so in order to find that, we really needed a probe (probe builder and launcher).”

Students used the expert tool as they designed their probes to learn more about the instruments they could include on their probes. One student said, “I chose the expert for the instruments. I wanted to know what information they would gather for me.” They used the notebook to record important information, to compare information they gathered, and to make note of potential home choices for the alien species as indicated by one student comment, “I just put down planets (in the notebook) that could not be possible choices for the species.”

The third set of tools used by the students was the control room, periodic table, concepts database, and notebook. Students used these tools as they moved into the third phase of problem solving: integrating information. Students viewed the results gathered from their probes in the control room and used the periodic table and the concepts database to help interpret these results. Students commented:

> “Once we got information back from the probes we saw that Pluto was not a good home, I had to look at the periodic table to make sure there was no water.”

"I'm not a science major and so some of the things they give us and stuff I went in there (concepts database) to check."

At this point, the students integrated the information they had learned about the aliens and the planets to confirm or eliminate potential solutions. Again, the notebook was often used in conjunction with these tools to record important information and to compare alien needs with planet characteristics. One student commented, "I was checking (in the notebook) to see if what I found out from the probe matched my criteria."

Finally, during the final stage of problem solving -- evaluating process and outcome -- students used many of the tools again for a second or third time and also used the solution form. They returned to the alien database to confirm information about the alien species or to the solar system database and probe launch room to review or gather more information about the solar system. For example, one student reported revisiting the alien database "to go back to see if it was really nitrogen that they ate or not." Another student reported using the solar system database towards the end of the problem-solving process because he "began to realize that this might not be the right place" and had "to go back and look for other possible choices". Another sent additional probes to "get a little more information." During this process, they reported they were simply trying to find the best possible home for the alien species, and they wanted to verify that their choice met the needs of the alien species. They reported their final decision in the solution form.

These results are consistent with the results of the Chi-square analyses. As students worked to "understand the problem", they reported using tools that "support cognitive processes," such as the notebook and the expert. They used tools that "support otherwise out of reach activities", such as the probe design and probe launch rooms, as they "identified, gathered, and organized important information," but not as they worked to "understand the problem." Finally, the control room, a tool that "supports hypothesis testing" was used as students "integrated information." The finding also confirmed the descriptive analysis that in later stages of the problem solving, students went back to use tools that share cognitive load and supporting cognitive processes (e.g. solar database, alien database, and notebook) to double check information and test their hypothesis. Figure 3 shows a visual representation of the stimulated recall data summary and the Appendix B provides a snapshot of the stimulated recall analysis showing the stages of students' problem solving, the tools they reported using at each stage, and examples of students' interview responses. Stimulated recall interviews highlighted the concurrent and repeated use of some tools. For example, although the notebook tool by its function would be expected to be used during the stage of "information gathering and organization," students actually reported to use it in connection with alien database during their "understanding the problem" and then revisited it during other stages of problem solving. This noted finding is confirmed in the analyses of all three data sources (see Figures 2 and 3 and Appendix B).

-------------------Insert Figure 3 Here -----------------

Cognitive Tool Use Patterns for Students with High and Low Performance Scores

To answer the research question, "Do college students with high and low performance scores use the cognitive tools in a similar way?" we grouped the students into high (N=20), intermediate (N=9), and low (N=19) based upon their performance scores and examined how three groups used the tools. MANOVA was performed with groups of students as the independent variable and diversity, consistency, and activeness of tool use as the dependent variables.

Students' tool use was defined along three dimensions: diversity of tool use, consistency of tool use, and activeness of tool use (Liu, et al., 2004). The *diversity* of tool use indicated the extent to which students used a variety of tools. This score could range from 1 to 13, representing the number of different tools the students reported using. If a student reported using an individual tool more than once, they would receive 1 point for that tool. A student who reported using all 13 tools more than once would receive a score of 13, indicating that they had used a wide variety of tools.

The *consistency* of tool use reflected whether students used a particular tool across all 20 cognitive processes. Students had to report using a tool for 10 or more cognitive processes (i.e., 50% or more), out of the 20 possible processes, for its use to be considered consistent. This score could range from 1 to 13, representing the number of different tools a student reported using consistently. If a student reported using a single tool for more than 10 cognitive processes, they would receive one point for that tool. A student who reported using all 13 tools 10 or more times would get a score of 13 points.

The *activeness* of tool use indicated the extent to which students reported high engagement in a cognitive process. That is, for how many of the 20 cognitive processing statements did a student indicate she engaged in it "all of the time" by marking a "5" on the Likert scale? If a student reported a "5" on the Likert scale for all 20 processing statements, she would receive a score of 20, indicating a high level of engagement in the cognitive processes. This measurement was developed and used in the previous study (Liu, et al., 2004).

The MANOVA revealed no overall significant differences in the diversity, consistency, and activeness of tool use by the three groups of students (F (6, 86) = 1.43, p = . 212; Wilk's Lambda = .827; partial eta squared = .091) (See Table 3 for the mean scores). The lack of difference in the diversity of tool use was aligned with the previous finding indicating that different performance groups responded similarly in terms of the number of different tools used (Liu et al., 2004). The lack of difference in the consistency and activeness of tool use indicated that one group did not report using the tools more consistently or actively than the other groups.

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Discussion

In this study we intended to further examine the connection between cognitive tool use and cognitive processes involved in solving a complex problem. With multiple data sources, both objective and subjective, the results of this study with college students confirmed the findings from previous two studies with sixth graders (Liu & Bera, 2005; Liu, Bera, Corliss, Svinicki, & Beth, 2004). The descriptive analysis, based on the log data, provided a visual representation of tool use patterns, indicating certain categories of tools were more dominant in use during different stages of problem solving (e. g. tools sharing cognitive load and supporting cognitive processes were more heavily used earlier), and there were indications (as shown in Figure 2) that students simultaneously used multiple tools while they were engaged in integrating and evaluating information. Results from the Chi Square analyses based upon the self-reported data showed strong connections between cognitive processes and cognitive tool use. Moreover, the stimulated recall data confirmed the findings from these two analyses and showed deliberate and careful use of tools by the students.

The tool use patterns indicated that early in the problem-solving process, tools which support cognitive processing and share cognitive load played a central role in helping students conceptualize the problem, and students used these tools to search, locate and select relevant information, and conduct research. Once they have formed initial hypotheses as revealed through the stimulated recall data, students' 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 are used more for reference in conjunction with the tasks of interpreting and organizing data and building a rationale (see Figure 2), yet, they are still important as students were integrating all pieces of information in generating solution to a complex problem. The findings suggested that the built-in cognitive tools in *Alien Rescue* helped students externalize and conceptualize problems, assisted in their understanding of the problem, and facilitated their strategic problem solving. The tool use patterns also demonstrated that certain tools are of more importance during different stages of problem solving, but students need tools of various functions to solve the problem and they are capable of using several tools simultaneously. Using the tools in various categories over the entire problem-solving process, students are given many opportunities to exercise higher-level thinking skills. The findings from this series of studies provided clear empirical evidence to support the theoretical notion that cognitive tools play an important role in assisting students' problem solving (Jonassen & Reeves, 1996).

The finding that there was no difference in the diversity of tool use by three performance groups suggested that different types of tools were needed and used by the college students in this study, as they were by sixth-graders in the previous research (Liu & Bera, 2005; Liu et al., 2004). In our previous study (Liu & Bera), we found that sixth-graders in the top third of their performance level made more appropriate use of the tools than those at the bottom third. The study by Liu et al. indicated that metacognitively oriented students reported using more tools in a consistent manner, and information processing oriented students reported a higher degree of activeness in their cognitive processes. This study intended to further investigate this issue but found no statistical differences. However, descriptively the mean differences in activeness of tool use showed that the middle and high performance groups reported to be more active in tool use than the low performance group (M_{low} =5.63, SD=3.62, M_{Mid}=8.78, SD=2.99, M_{High}=7.7, SD=3.80) (see Table 3). Interesting questions emerged: Will students with different characteristics use the tools differently and will more strategic, appropriate, and active use of the tools contribute to the students' performance scores (Bera & Liu, 2006, Liu, Bera, Corliss, Svinicki, & Beth, 2004)? The inconclusive finding from this and previous studies highlights the significance of research on cognitive tools use and calls for further studies examining the relationship between tool use and performance and on strategies to support learners' productive use of tools in their problem-solving process. In our future research, we intend to further investigate such a relationship with different measures.

Oliver and Hannafin's study (2000) revealed that students may not be aware of the functions of tools and failed to use them to their full potential. Contextualized use of cognitive tools is an integral part of instruction (Jonassen & Reeves, 1996; Kozma, 1987; Lajoie, 1993; Pea, 1985; Salomon, Perkins, & Globerson, 1991). In *Alien Rescue*, each tool performs a specific function and is needed at different times during the problem-solving process. It hoped that students would realize the importance and relevance of the tools and use them appropriately. By integrating both objective and subjective data sources, this study confirmed what we have observed in the previous studies: that the students were aware of the tool functions and selected the tools relevant to the problem-solving stages.

The increasing use of multiple tools from early stages to later stages of problem-solving, as shown in previous studies and confirmed in this study, is another indication that the students not only became comfortable in using the tools, but also realized how different tools can be used together to solve the problem. The stimulated recall data clearly indicated students' rationale to access multiple tools when they were integrating and evaluating the information. In *Alien Rescue*, although the tools are present all the time, the selection of tools is entirely the students' decision. Becoming acquainted with the nature, function, and timing of all tools available requires students to be strategic in their problem solving, especially when they were given a limited amount of time as in this study. Students must continuously exercise their decision-making and evaluation skills to see which tools to use, when, and why. Given all resources available, students are challenged to make connections and regulate conditions for their own learning.

Complex learning environments with student-centered foci, such as *Alien Rescue*, need different cognitive tools embedded within them as scaffolds to facilitate learning (Pellegrino, 2004). In examining how sixth-graders use cognitive tools in *Alien Rescue*, there is evidence that tools assisted the sixth-graders' problem solving. However, teachers were also another critical element in their facilitation of sixth-graders' learning. So to what extent do the tools themselves provide scaffolding? In this study, the results from a more controlled "laboratory study" clearly indicated that tool uses mediated college students' problem solving without teachers' intervention. In complex learning environments, however, cognitive tools are only one instructional variable among others that create the conditions for learning (Salomon, 1993). According to Salomon (1993), learning is far more of a distributed process than we have conceded in the past. Kim and Reeves (2007) proposed that the learner, cognitive tools, and a meaningful task together form a joint system of learning. Our previous study offered some preliminary indication that individual differences, and group processing can also interact during students' problem solving (Bera & Liu, 2006). To what extent can a system of instructional variables then be combined to support group learning and individual cognition?

Given the findings of this study and previous ones, our next steps are to further examine 1) the relationship between tool use and performance and learner characteristics, 2) the design of a few heavily used tools (e.g. notebook), 3) the interaction of multiple instructional components to facilitate learning, and 4) tool use patterns of more advanced learners (graduate students in science majors) to investigate how they use the tools to assist their problem solving. The goal of this program of research is to gain further insights on how experienced learners use the tools and how cognitive tools can be designed and implemented to support novice learners (i.e. sixth-graders) in problem solving. We intend to investigate how various contextual factors such as learning tasks, learners' performance and cognition, group learning, and experience can mediate learning in connection with cognitive tool use. It is the interaction of these contextual factors and the manipulation of these factors that can create an optimal learning situation.

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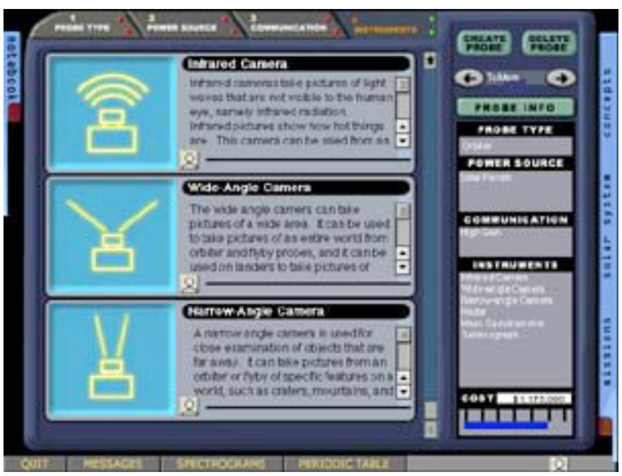
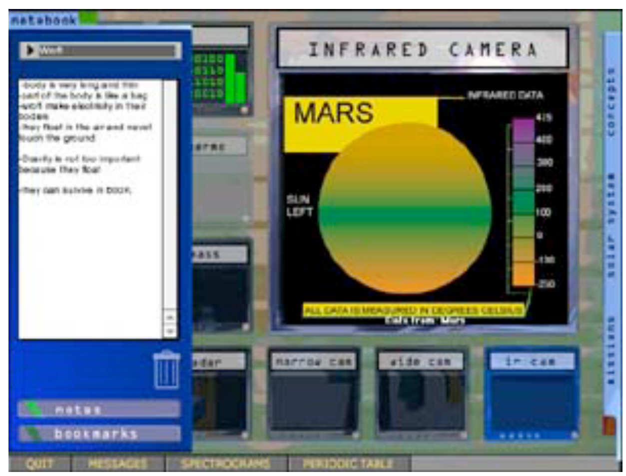
Figure 1. Screen Shots Showing Some Cognitive Tools Provided In <u>Alien Rescue.</u>

(a) Alien Database

(b) Access Solar Database while in Alien Database



(c) Probe Builder Room



(d) Access Notebook tool while in Control Room and viewing data

Figure 2. Frequency of Tool Use Over Time by Tool Category

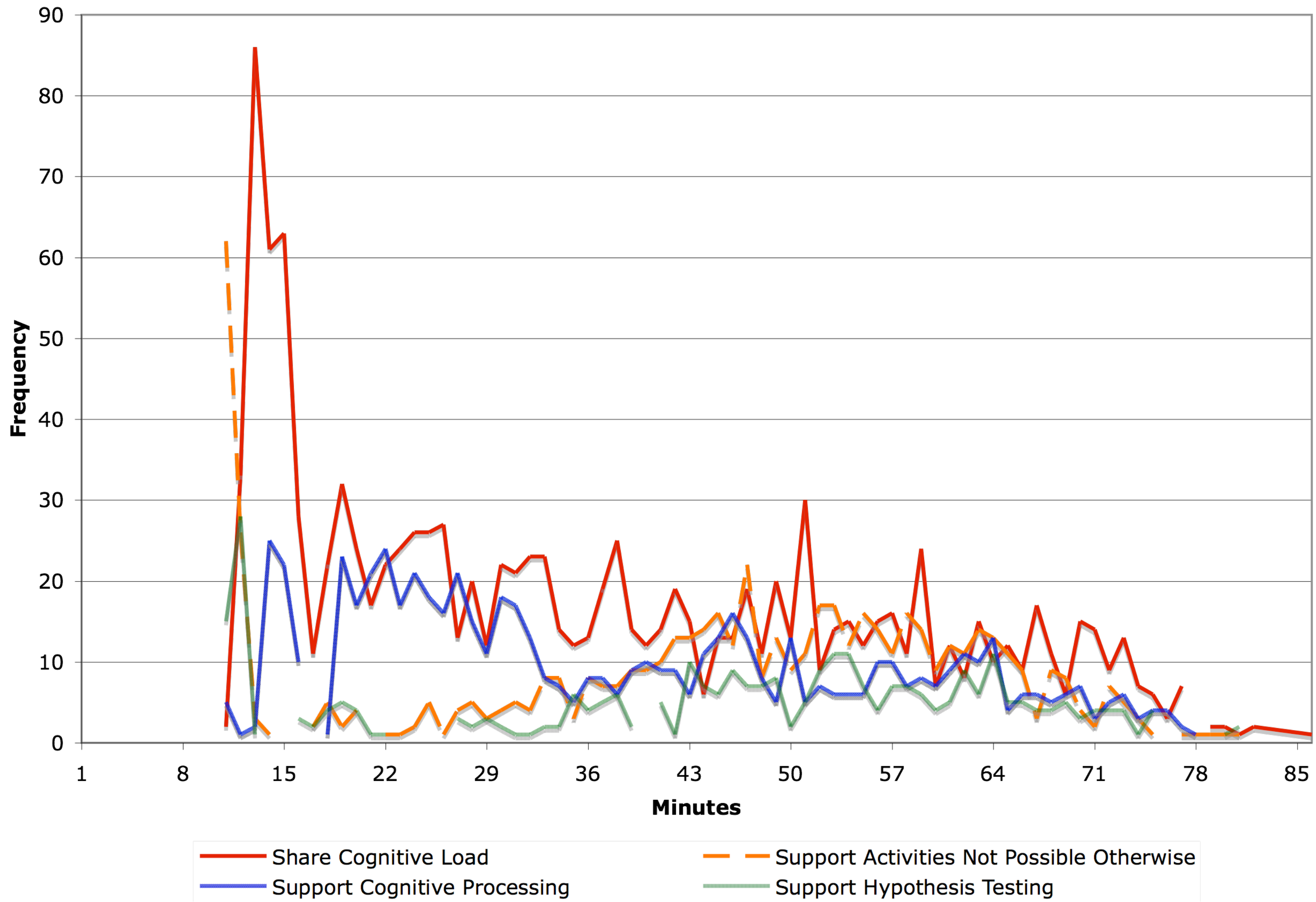


Figure 3. Connection Among Tool Use, Cognitive Processes, Students' Reasoning As Shown in Stimulated Recall Interviews

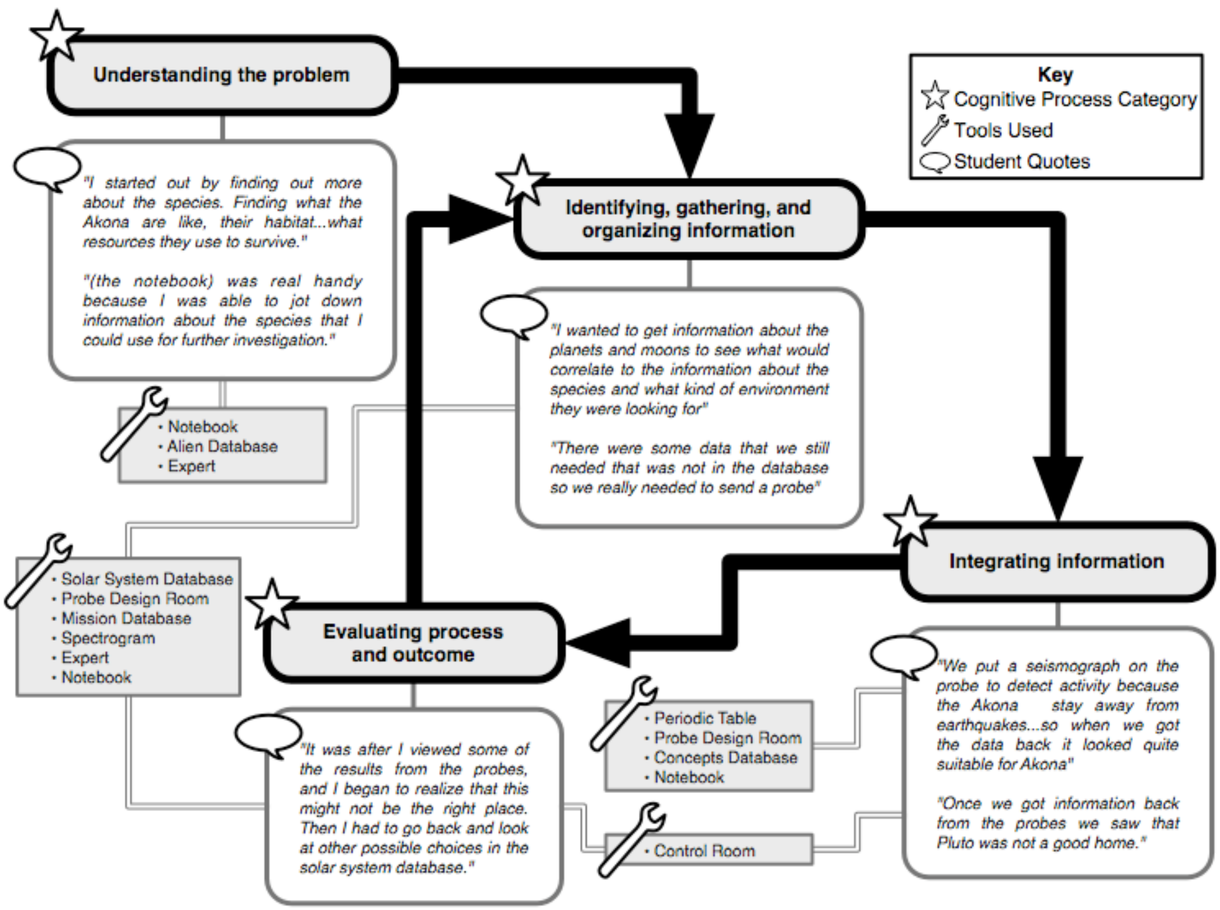


Table 1.

Duration and Frequency of Cognitive Tool Use As Shown in Log Data

	Frequency			Duration (seconds)		
Tools that:		% Category	% Total		% Category	% Total
Share Cognitive Load						
Alien database	**152**	12.41%	5.46%	**13,120**	16.46%	8.81%
Concept database	122	9.96%	4.38%	4,673	5.86%	3.14%
Mission database	**468**	38.20%	16.82%	7,136	8.96%	4.79%
Periodic Chart	65	5.31%	2.34%	509	0.64%	0.34%
Solar database	**272**	22.20%	9.77%	**51,222**	64.28%	34.41%
Spectrogram	146	11.92%	5.25%	3,026	3.80%	2.03%
Subtotal	1,225			79,686		
% of total tool use	44.02%			53.54%		
Support Cognitive Processing						
Bookmarks	45	6.81%	1.62%	687	2.88%	0.46%
Expert	54	8.17%	1.94%	870	3.65%	0.58%
Notebook	**562**	85.02%	20.19%	**22,296**	93.47%	14.98%
Subtotal	661			23,853		
% of total tool use	23.75%			16.03%		
	Frequency			Duration (seconds)		

		%	%		%	%
Tools that:		Category	Total		Category	Total
Support Activities Not Possible Otherwise						
Probe Builder	**311**	53.34%	11.17%	**28,004**	94.87%	18.81%
Probe Launcher	**272**	46.66%	9.77%	1,513	5.13%	1.02%
Subtotal	583			29,517		
% of total tool use	20.95%			19.83%		
Support Hypothesis Testing						
Control Room	**275**	87.58%	9.88%	**15,048**	95.33%	10.11%
Solution Form	39	12.42%	1.40%	737	4.67%	0.50%
Subtotal	314			15,785		
% of total tool use	11.28%			10.61%		

Table 2.

Results of Chi Square Analysis on Association between Cognitive Tool Use and Cognitive Processes.

	Cognitive Processes				
Tools that Support	Understanding	Identifying, Gathering, Organizing	Integrating	Evaluating	Total
Cognitive Process					
Count	341.0	351.0	327.0	390.0	1409.0
Expected Count	287.2	427.1	323.7	371.0	1409.0
Adj. Std. Residual[+]	5.1*	-6.3*	.3	1.6	
Cognitive Load					
Count	101.0	139.0	97.0	136.0	473.0
Expected Count	96.4	143.4	108.7	124.6	473.0
Adj. Std. Residual[+]	.6	-.5	-1.4	1.3	
Activities Out of Reach					
Count	74.0	277.0	124.0	132.0	607
Expected Count	123.7	184.0	139.4	159.8	607
Adj. Std. Residual [+]	-5.7*	9.3*	-1.7	-2.9*	

Tools that Support	Cognitive Processes				
	Understanding	Identifying, Gathering, Organizing	Integrating	Evaluating	Total
Hypothesis Testing					
Count	42.0	63.0	81.0	63.0	249.0
Expected Count	50.7	75.5	57.2	65.6	249.0
Adj. Std. Residual+	-1.4	-1.8	3.8*	-.4	
Total					
Count	558	830	629	721	2738
Expected Count	558	830	629	721	2738

+ Adjusted Standardized Residuals is the residual for a cell (observed minus expected value) divided by an estimate of its standard error. The resulting standardized residual is expressed in standard deviation units above or below the mean. Two standard deviation units greater than or less than the mean indicates a significant deviation.

Table 3.

Diversity, Consistency, and Activeness of Tool Use

	Mean	*SD*
Diversity		
Low	6.95	2.22
Medium	7.56	1.51
High	7.30	1.59
Total	7.21	1.83
Consistency		
Low	1.21	1.55
Medium	1.89	1.27
High	2.45	2.28
Total	1.85	1.90
Activeness		
Low	5.63	3.62
Medium	8.78	2.99
High	7.70	3.80
Total	7.08	3.74

Appendix A

Items 1-3 to Illustrate the Formatting of the *Cognitive Task Questionnaire*

Instructions:

1. Read the statement on the left first. Circle the number that best describes what you did when using Alien Rescue.
2. For **<u>each</u>** statement, think about which part(s) of Alien Rescue you used that helped do that activity. Put a check mark under each tool that helped you to do the activity. You can check as many boxes as you like. If you did not use any tools, then do not put a check mark.

	alien database	solar system database	mission database	concept database	periodic chart	spectrogram	notebook	bookmark feature	expert tool	probe builder	probe launcher	control room	solution form
1. I took time to explore the rooms and tools in Alien Rescue before I began searching for a new home for the Aliens. 1 2 3 4 5 Not at all Sometimes All the time													
2. When using Alien Rescue, I first thought about the problem I needed to solve and figured out what I needed to do. 1 2 3 4 5 Not at all Sometimes All the time													
3. When I took notes on the aliens and solar system, I knew what I needed to do with this information. 1 2 3 4 5 Not at all Sometimes All the time													

alien database solar system database mission database concept database periodic chart spectrogram notebook bookmark feature expert tool probe builder probe launcher control room solution form

Appendix B

Snapshot of Stimulated Recall Interview Results

Stages in Problem Solving	Tools Used	Tool Category	Description of Tool Use	Interpretation	Sample Quotes
Understanding the problem	Alien database *Often the Notebook and Expert were used along with the Alien database	Share cognitive load	-Gather information about the species -Get an overview of the problem and some general information	Overall, the first tool students used was the alien database. This gave them an overview of the problem and information about the alien species they would need in order to solve the problem.	"Well, I started out by finding out more about the species. Finding what the Akona are like, their habitat what they…what resources they use in order to survive and things like that." "It gave me a background"
	*Notebook	Support cognitive processes	-Record important information about alien's needs for easy access later	As students read the information in the Alien database, they often took notes on important information in the Notebook.	"…but I used the notebook instead, so I wouldn't have to refer back…to go back to the same spot each time. It was real handy because I was able to jot down information about the species that I could use for further investigation."
Identifying, gathering and organizing important information	Solar System Database	Share cognitive load	-Find information about planets -Match planets with	Once the students learned what the aliens needed to survive, they went to the	"I wanted to get some information about the different planets and moons to see what kind of information they

			alien needs	Solar System Database to find places that would meet the aliens' needs.	had that would correlate to the information about the species and what kind of environment they are looking for. "
	Probe design & launch	Support otherwise out-of-reach activities	-Gather additional information about the planets -Look for specific things needed by the aliens	Students designed and launched probes to gather additional information they needed about the planets and moons in our solar system in order to find a good home for the aliens.	"There were some data that we still needed just to make sure that this was a good match for the Akona…for example, the seismic activity was not in the database and so in order to find that, we really needed a probe"
Integrating Information	Control room	Support hypothesis testing	-Assess error messages; learn how to design appropriate probes -Compare results with alien needs -Eliminate bad choices of planets; confirm good planet choices	Students viewed the data gathered from the probes they sent in the Control Room. Here they either obtained the information they needed to eliminate or confirm potential home choices, or they received error messages they needed to interpret to determine why their probe failed.	"On the first one I used a battery charger and a low radar…when I went to the control room and tried to look at my results, there wasn't a lot. It said that information was not attainable." "we put a seismograph on it to detect activity because the Akona prefer to stay away from earthquakes…so when we got the data back it looked quite suitable for Akona."

					"Once we got information back from the probes we saw that Pluto was not a good home."
Evaluating Process & Outcome	Probe design & launch – Time 2	Support otherwise out-of-reach activities	-Remedy errors from previous probe -Gather additional information about the planets that wasn't gathered with previous probes -Gather information about new planets because previous probes helped to eliminate previous planet choices	Students often sent more than one probe. They either corrected a mistake made on a previous probe, sent probes to multiple planets and moons, or sent multiple probes to the same place with different instruments each time to gather different data.	"I was anxious to find the right tool. I sent out a probe to Venus, and I directed some of the equipment that did not, I guess correlate with my mission preference. I guess I used a fly-by or something like that, instead of orbiting, and so the message it gave me was "Message Malfunction" or something like that."
	Solar System Database – Time 2	Share cognitive load	-Gather more information about the planets -Find a new planet that might be a good match, when	If students did not get the results they wanted from their probes, they sometimes went back to the Solar System Database to consider other	"It was after I viewed some of the results from the probes, and I began to realize that this might not be the right place. Then I had to go back and look at other possible choices

	previous planet choice was eliminated based on probe results -Double check that planet met all of alien's needs	places as suitable homes for the alien species. Another reason they returned to this tool was to double check the place they chose truly met all of the aliens' needs.	in the solar system database." "I wanted to make sure that I had the four things that the aliens needed and the four matching elements from Triton. I had to visually make two columns that I could see."