Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Computers in Human Behavior 23 (2007) 664–704

Computers in Human Behavior

www.elsevier.com/locate/comphumbeh

The role of computer tools in experts' solving ill-structured problems

Kausalai Kay Wijekumar [a,*], David H. Jonassen [b]

[a] *The Pennsylvania State University Beaver, 143 Administration Building, 100 University Drive, Monaca, PA 15061, USA*
[b] *The University of Missouri, 221C Townsend Hall, University of Missouri, Columbia, MO 65211, USA*

Abstract

The focus of this study is first, the qualitative changes within the human agent as a result of extensive computer tool use (over 5 years), also described as the effect of tool use [Pea, R. D. (1985). Beyond amplification: using the computer to reorganize mental functioning. *Educational Psychologist*, *20*(4), 167–182; Salomon, G. (1990). Cognitive effects with and of computer technology. *Communication Research*, *17*(1), 26–44], and second, the "quantitative changes in accomplishment" of the human agent in the presence of computer tools, also described as effect with-tools [Pea (1985, p. 57); Salomon (1990)]. This research used ill-structured problem solving as the task and experts with more than 6 years of domain and tool experience to document the changes in their knowledge structures. The study also compared the differences between the ill-structured problem solving with and without the computer tool to identify differences that may be a result of the computer's presence.

Keywords: Computers and media; Cognitive science; Conceptual knowledge; Problem solving

---

[*] Corresponding author. Fax: +1 412 749 4578.
E-mail addresses: kxw190@psu.edu (K.K. Wijekumar), jonassen@missouri.edu (D.H. Jonassen).

0747-5632/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.chb.2004.11.004

1. Introduction

The research presented in this paper brings together three important lines of research dealing with computers and their impact on human knowledge structures, ill-structured problem solving, and expertise.

First, our concern is about computers and their impact on human activities. What humans have learned from using computers has been described as the "*effect*" of computer use (Pea, 1985; Salomon, 1990; Salomon, Perkins, & Globerson, 1991). How this knowledge affects future behaviors in the presence of tools is described as the "*effect with*" tools (Pea, 1985; Salomon, 1990; Salomon et al., 1991). A key question involves how individuals acquire the computer skills (effect of) and how these skills affect their future behaviors.

Second, research on ill-structured problem solving has documented how these everyday types of problems are different in structure, problem solving strategies, skills, and outcomes (Hong, 1998). Ill-structured problems are vague, have multiple constraints, are affected by the context, and have multiple possible solutions. The problem solver requires skills in understanding the complexities of the problems, identifying multiple constraints, selecting one of many solutions, and justifying the solution (Jonassen, 1997). Computers can play an important role in the solving of ill-structured problems. They can serve as an information source, a tool for number crunching, a tool to develop alternative solutions, and a tool for constructing arguments for the solutions. The question that we sought to answer was how the computer tool was used in ill-structured problem solving.

Third, expertise research on ill-structured problem solving has identified how experts' domain knowledge is organized, solve problems using forward reasoning, recall chunked information from past experiences to narrow options, and create effective and lengthy justifications for their solutions (Voss, Greene, Post, & Penner, 1983). Our research focus was how computer tools affect the experts' knowledge structures and ill-structured problem solving.

We were interested in bringing together these three areas of research to study how experts acquire computer tool skills, how these skills affect their ill-structured problem solving, and whether there were any differences in their problem solving in the presence or absence of the computer tools. For example, when a domain expert in Economics has used statistical analysis tools for over 6 years: have his/her knowledge structures changed as a result of the use?, does he/she rely on the statistical analysis tool to solve problems?, does he/she construct solutions by relying on the tools?, are his/her solutions different when there is no tool?

1.1. *Effect of and effect with computer tools*

1.1.1. *Effect of*

The *effect of* computer use is described as the reorganization of the mental functions of the learner (Pea, 1985) and the cultivation, development, or even acquisition of cognitive skills from technology use (Jonassen, 2000; Salomon, 1990). Repeated use of calculators, word processors, spreadsheets, databases, modeling tools, statistical analysis tools, computer supported collaboration tools, and graphical design tools may allow learners to gain understanding of knowledge differently, approach problems differently, and apply these skills in new situations differently (Perkins, 1985). Just as schooling and classroom teaching techniques have changed how students solve problems, computer use may also contribute to change how learners store, organize, retrieve, and use knowledge.

1.1.2. Effect with

Effect with tools is the "quantitative changes in accomplishment" (Pea, 1993, p. 57) in the presence of tools. This change can be a result of off-loading and/or affordances (Pea, 1993, p. 51). Salomon (1990, p. 30) refers to the *effect with* phenomena as "qualitatively redefining the very nature of the task" from learning about to creating and controlling the task.

First, computers serve as mechanical workhorses to which users off-load mental tasks. Since "memory load is one of the main roadblocks to higher level thinking, and given that higher order thinking assumes automatization of lower level skills," (Olson, 1988; Anderson, 1983 in Salomon (1990, p. 29)) computers may provide the support necessary to help learners perform expert like tasks. These expert like tasks include hypothesis testing, seeking solution alternatives, forecasting, and evaluation of options, instead of concentrating on the numerical calculations or trying to solve equations.

Second, the computers prompt the solver and lead them to take action or gauge complexity of situations. This rather complex interaction between the tool and its user is sometimes described as "affordances" (Gibson, 1966; Pea, 1993). Zhang (1997) suggests that the problem presentation method may "restrict, dictate, and guide" solvers. Salomon (1990) describes the intellectual partnership afforded by the tool as one where the program affords or constrains behaviors and the learner must accept or take what is provided by the tool.

1.1.3. Research on the effect of

There are two research themes that relate to the *effect of* computer tools.

The first line of research explicitly studies the effect of computer tools on problem solving. Research on a computerized reading partner (Salomon, Globerson, & Guterman, 1989) found that seventh grade students do internalize the metacognitive strategies and are able to transfer those skills to new applications in delayed tasks several months later (Salomon et al., 1989).

The second line of research studies showcase computers and their use in mathematics (Dixon, 1997; Mayes, 1995), chemistry (Williamson & Abraham, 1995), geography, physics (de Jong et al., 1999), and engineering (Canizares & Faur, 1997; Lindström, Marton, Ottosson, & Laurillard, 1993). These studies produced conflicting results that may be explained based on the tasks, tools, strategies, and outcome measures. The conclusions from these studies were that the short-term impact of the computer tool depended on the task, learners, and particular tools.

These studies that concentrated on novices using computer tools for less than a year do not help us answer the questions about what impact long-term computer tool use has on users' knowledge structures, and how these experiences affect their problem solving strategies.

1.1.4. Research on the effect with

The research on the *effect with* computer tools comes from a distributed cognition genre. These studies showed how tools and humans interact by observing real-life situations. They have documented the interactions between humans and the tools but did not focus on the knowledge structures of the actors and how the knowledge structures affected the problem solving situations. A special note is made here because this line of research makes strong assumptions about the nature of activity and focuses on the actions and not what happens within the minds of the actors. This paper contends that there is no distribution of cognition without the individual's cognition and the individual's cognitive structures are important to study.

The effects of off-loading and affordances are evident in the current research on tools and problem representations. A qualitative analysis of observed interactions in the London underground system showed users off-loading mental tasks like managing a large number of trains on the underground using a timetable and computer aided navigation (Heath & Luff, 1998). The observations show that using closed circuit televisions, and three monitors with line diagrams of train locations, the controller and other information managers monitor and discriminate between actions to control the smooth running of the trains.

Another qualitative study also provides some evidence of off-loading and affordances using videotapes of a cockpit crew and the instrumentation during simulated aircraft landings and take-off (Hutchins, 1995; Hutchins & Klausen, 1998). Pilots were prompted to perform different actions by gauges in the cockpit, and they also used historical artifacts like charts (from previous landings) to gauge weight, speeds, and instrumentation settings. Examples include expediting the climb of the airplane by maximizing the thrust using the instrumentation panel to find the appropriate engine pressure ratio values. The gauges also continuously update the values of the current air temperature and altitude to aid in this activity.

The concept of affordances have been researched in games (Zhang, 1997) and computer interfaces (Norman, 1988). Roth (1995) & Roth et al. (1996) conducted studies on affordances provided by a computer simulation tool called Interactive Physics™ in 11th grade science education. They found that the computer representations had to be explained to the students (to prevent misinterpretations), and sometimes hindered the learners by guiding them into the wrong approach. Carter, Westbrook, & Thompkins (1999, p. 89) studied 26 ninth grade students interacting with electronic circuit design tools like circuit boards, multimeters, and graphing calculators. They found that "if the tools was outside their zone of proximal development, students could not use the tools to develop an understanding of circuits".

Based on these research findings, we may suggest that in the presence of tools or when isomorphs (multiple representations) of the same problem are presented, users behave differently. The behavior changes include:

- Remembering how, when, and where to use external resources to find information instead of trying to store everything within their own brain (Henning, 1998; Hutchins, 1995).
- Organizing of problem solving activities to include reliance on the tool to keep track of the history of the activity, relying on the tool to conduct some computational tasks, and expect the tool to prompt certain activities (Heath & Luff, 1998; Hutchins, 1995).
- Understanding the functions of the tool in relation to the domain related problem-solving activities (Henning, 1998; Kozma & Russell, 1997).
- Unknowingly being led to take certain actions or conceptualize problems as being more difficult (Roth, 1995; Roth, Woszczyna, & Smith, 1996; Zhang, 1997).
- Not attending to some important cues from the tools available because of a lack of training or familiarity with the tools or sense of perceived need (Morgan, Herschler, Wiener, & Salas, 1993).
- Accepting the affordances provided by the tool only when they (learner or user) have the pre-requisite knowledge (Carter et al., 1999).

Our first purpose was to address these theories by studying the long-term cognitive impact of a particular computer tool like statistical analysis packages to document how the users' knowledge structures have changed and then study how these changes affect their ill-structured problem solving approach and solution.

1.2. Ill-structured problem solving

Ill-structured problems were chosen for this study because they are more complex and require a different set of problem solving skills than well-structured problems. Ill-structured problem solving has also been identified by schools and other research organizations as a critical skill for educators to concentrate on (National Research Council, 1996).

Tools can reduce the cognitive load of ill-structured problems (Salomon, 1990) by off-loading mechanical computing tasks or creating alternative representations of data like graphs and charts, creating forecasts based on the economic data, and allow the solver to concentrate on testing hypothesis (Pea, 1985). The tools can also be used to project impact of possible solutions, and even contribute to the justification of proposed solutions. Depending on the tool experiences of the problem solver, the tool may also constrain their behaviors (Kozma & Russell, 1997) and prompt them to seek solutions involving the use of the tool.

Based on these issues, the second purpose of this study was to identify how tool experience affects experts representing ill-structured problems and how the presence of the tool affects/affords the problem representation.

1.3. Expertise

Expertise research has contributed a wealth of knowledge about how many years it takes to gain expertise, how experts' domain knowledge is organized, and how this organization of domain knowledge affects their approach to problem solving. In ill-structured problem solving experts were shown to conduct forward reasoning, identify multiple constraints to problems, and provide lengthy justifications to their solutions (Voss et al., 1983).

Think-aloud protocol collection and analysis research methods used in these expertise research studies were also most appropriate for studying knowledge structures of participants (Ericsson & Simon, 1999).

Research on ill-structured problem solving and expertise (Voss, 1988; Voss et al., 1983) showed that experts established factors responsible for the problem by decomposing the problem and then converting the sub-problems into solvable problems. The experts' ill-structured problem representation dictated the solutions and they sought few alternatives. Patel & Groen (1991) showed that experts conducted forward reasoning in medical diagnostic tasks. Lesgold et al. (1988) studied how experts and novices diagnosed from X-ray pictures and found that experts retrieve and use their schema faster, flexibly, and effectively. While these studies all used ill-structured problems there were few external artifacts/tools and they were not the focus of the studies. Experts in Lesgold et al. (1988) used X-ray pictures but the research did not focus on their (X-rays) role in the problem solving process.

The controlled experiments conducted on experts solving ill-structured problems concentrated on the domain knowledge. Our third purpose was to extend this and study not only domain knowledge but also how domain knowledge is combined with tool knowledge/skills.

1.4. Research questions

Therefore this study seeks to infer how long-term tool experience by domain experts is represented using think-aloud protocols while solving ill-structured problems. Comparing how problems are represented with- and without-tools allows us a view of the affordances of the tools. The research questions were:

1. How are long-term statistical analysis tool experiences (*effect of*) blended with domain knowledge in experts' knowledge structures?
2. How are the functions and roles of the statistical analysis tool conceptualized by experts?
3. How do domain experts with long-term statistical analysis tool use represent ill-structured problems in the presence of statistical analysis tools (*effect with*)?
4. How do domain experts with long-term computer tool use represent ill-structured problems without computer tools?
5. Is there a difference in experts' representation of ill-structured problems with and without statistical analysis tools (affordances)?

The ill-structured problems are in economics and management, and the computer tools are statistical analysis software packages like SPSS, SYSTAT, and Excel.

2. Methods

The participants in this study were college professors from two public universities in northeastern US and alumni of the universities who were professionals with advanced degrees in their domains and working in consulting roles. Purposive sampling was used to select participants with experience in problem solving and tool use, and holding advanced degrees in the domains of the chosen problems (economics and management). Examples of the kinds of data analysis required to solve problems included regression models and correlations between factors.

Participants were recruited from economics and management domains. Twenty-three respondents volunteered to participate. Of the 23 volunteers, three were dropped from the study because they did not meet the minimum tool experience for the study. The remaining 20 participants were from the management and economics domains.

These participants were identified as experts in their domains based on their advanced degree, years of service in teaching or other professional roles, and extensive tool experience. This process and criteria were similar to those used by Ericsson & Simon (1993, 1999), Ericsson & Smith (1991), and Chi, Feltovich, & Glaser (1981). All participants had a minimum 6 years of experience in college level teaching and research and professional consulting experiences with an average number of years of experience of 18.55.

The participants had used statistical analysis tools for at least 5 years in their domains. Experience on the specific computer tools used, such as SPSS, SYSTAT, Excel, was collected in a preliminary survey. Every participant had used at least one of the tools chosen for this study within the past year for professional work, teaching, or research purposes. There were differences in the frequency of tool use. Eight of the participants (40%) used statistical analysis tools daily and all others used it weekly or monthly.

Demographic data on the participants showed there were two female experts (10%). The ethnic breakdown of the participants was 14 white Caucasians (70%), five Asians (25%), and one African American (5%).

2.1. Instruments

The materials for this study consisted of a pre-experiment questionnaire, pre- and post-experiment interview questions, instructions to the participants – sample think-aloud, and two problems used for the think-aloud.

2.2. Pre-experiment questionnaire

The questionnaire was designed to collect information about the subjects' familiarity with computer tools and their functions without influencing the think-aloud process. These data were used in the qualitative analysis to match the frequency with which tool functions were mentioned in the think-aloud problem solving process. The questions were adapted from McKeague (1996).

1. Amount of time that you have used computers? (0 years, 0–6 months, ldots)
2. Check all the software packages you have used and complete the name of the packages you have used:
   - Word processing ______________
   - Statistical analysis ______________
   - Spreadsheets ______________
   - Programming languages ______________
   - Web-search utilities ______________

   In order to identify the specific functions the participants have used, a third question was added regarding some commonly used functions in the computer tools. Some functions that could not be used in the current problem solving were also included so that outcome was not influenced. The functions that may be used in the problem solving are marked with an asterisk below.
3. Circle any of the following functions of software packages you have used within the past year?
   (a) Read data file
   (c) Create graphs from data*
   (e) Generate correlations*
   (g) Generate frequencies*
   (i) Generate regression*
   (k) Split data files
   (m) Create PowerPoint slides
   (b) Computer totals in spreadsheet*
   (d) Analyze trends
   (f) Generate ANOVAs
   (h) Create web pages
   (j) Insert hyperlinks
   (l) Post hoc analysis
   (n) Create a word document

A fourth question was added to identify the participants' familiarity with ill-structured problems similar to those used in the think-aloud process. Six example cases like "manufacturing problem" were described to the participants and they were asked whether they had used similar problems in teaching or other professional work. Again, unrelated example cases were presented to the participants in order to avoid influencing the outcomes.

2.3. Interviews

Three interviews were held with all participants. The first interview (pre-problem solving) was used to elicit information from participants on their conceptualization of statistical analysis tools. During the initial interview, the following questions were asked and answers were compiled.

1. What strategies do you usually use in problem solving?
2. What types of computer tools have you used? How often?
3. How do you use tools and where are they useful and not useful?

The second (post problem solving) interview was conducted with all participants to review/clarify the contents of the think-aloud tapes as well as gaining specific information regarding prior experiences in similar problem solving situations. The questions included:

1. Have you previously solved problems similar to those you solved in these activities? If you have, please list some of the characteristics of such problems and which of the two problems were they related to.
2. Did you use strategies that you use in your domain to solve these problems? If you did, please list them?
3. Was the computer tool necessary for the problem solving process? Explain why it was necessary or not.

The third interview was completed in two parts to verify the coding of the data by the two independent raters and researcher. First, a more complete interview was conducted with three participants, reviewing all their verbal data and the codes associated with them. During the session, participants were shown printed sheets of the transcribed verbal protocols and the right margin had the codes assigned to each segment. Participants were asked if the interpretations of the coders were consistent with their intentions and approach. Hill & Hannafin (1997) used a similar procedure where the subjects viewed their video taped think-aloud process after one week and clarified the interpretation of the researchers. Second, a shorter interview was conducted with the 17 other participants using coded segments where there was most disagreement between the raters. When the raters had different interpretations that could not be resolved through discussion, the segments and their interpretations were discussed with the participants.

2.4. Think-aloud protocols

Verbal protocols were collected during 1 h long think-aloud problem solving sessions with experts. While solving each of the problems, each participant thought aloud. Each think-aloud was audio taped. The audio taped data was transcribed and analyzed.

The process of coding the data used verbal data analysis procedures described by Chi (1997) and is described next.

1. The think-aloud data was transcribed. Selection of the passages or segments was done by reviewing the whole transcription and eliminating non-content verbalizations. The problem space, domain knowledge, solution, and tool use were identified as the initial set to be studied.
2. The segmenting of the transcription was done using a granularity of ideas and/or sentences. This varied according to the sequence of the protocol and was reviewed by the raters. The segments were sentences and/or concepts that directly relate to the areas of problem representation, domain knowledge, solution, and tool use. The coding scheme developed is presented in Table 1. The scheme was generated from findings reported by Chi et al. (1981); Voss et al. (1983), and the pilot study cataloging most of the possible representations and advice from the creator of the problems.

Table 1
Verbal protocol analysis scheme and examples

Category	Code	Example
Problem space		
	Known problem factor	For instance, here I see income, gender, and highways, they are useful factors
	Seek information	We need to get more information on the quality of students
	Interpret problem	In terms of solving this, I notice the key thing here is that her request is based on how efficient she is
Solution		
	Solution alternative	This principal is not deserving of a merit raise
	Solution argument	Based on the information provided on efficiency, a raise cannot be justified
Domain		
	Theory	This problem is one of economies of scale
	Assertion	The higher the number of students the average cost goes down if the fixed costs are high
	Reasoning	Since this is the largest school it makes sense that the principal can have low costs
Tool and analysis		
	Test hypothesis	On per capita income, I would expect it to have a positive impact on sales
	Analysis	This model shows 91% of the variation in sales is explained by these five factors
	Data transformation	I will create a new column and call it total cost and it will contain and equation that multiplies the number of students by the per student cost
	Tool function	I will run a regression and see
	Visualize	I am highlighting the high correlations. I am going to graph the data and see where the principal's school falls in comparison to others

3. Each utterance in the think-aloud protocols were grouped according to conceptually similar functions: problem space (known factors, new constraints identified, interpreting problem), domain knowledge (theory, assertion, reason), tool analysis (hypothesis testing, analysis, tool function, visualization), and solution (solution alternative, solution argument).
4. Each cell contained the statement number (the order of mention) as well as the relevance of the subject's statement (measured by the researcher and two independent raters working with the multiple protocol analysis software (MPAS)). MPAS presents the segmented protocols to raters and allowed them to objectively code the verbal segments. The raters reviewed the segments presented by the MPAS system and scored the relevance of the statement and identified the category from Table 1 under which the segment should be listed.
5. Two independent raters trained using the pre-defined codes and examples and the researcher coded each protocol. The correlation between raters was 0.72 after the first coding, but after discussions to reconcile differences the correlation

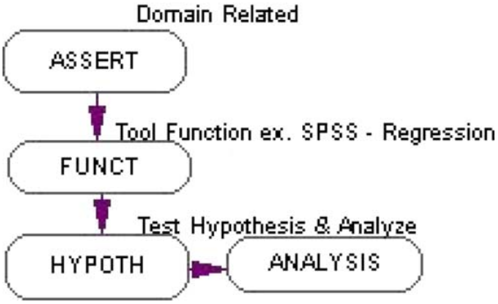

Fig. 1. Network diagram of verbal protocols.

increased to 0.93. Consensus was reached when the protocols were reviewed with the experts.

6. The coded data were graphed using a tree structure for the sequence of problem solving process (Fig. 1). The order of mention of domain knowledge and tool use was compared in the qualitative analysis.
7. The numeric codes were used to identify the weights (frequencies) of the different cells within the table. Comparisons between with-tool and without-tool conditions were done using standard statistical tests.

Qualitative comparisons of the data were made using network diagrams of the coded verbal protocols. These network diagrams contained nodes (coded verbal protocols) and links. The same coded verbal protocols used in the statistical comparisons were used to produce these diagrams. The sequences of the protocols were also captured using the links. For example when an expert presented a domain related assertion followed by using the tool, the diagram was designed with the ASSERT node followed by a FUNCT node. These diagrams allow a visual comparison of order of problem representation as well as hierarchy (domain knowledge or tool appearing first in the protocols). Fig. 1 shows the diagram corresponding to the protocol described above.

2.5. Ill-structured problems

The two problems chosen were selected based on the criteria for ill-structured problems and were used with permission from the creator (Appendix A). They are context dependent, have unknown goals, and unknown factors in the problem statement that must be inferred from the information or prior knowledge. There are also no pre-defined criteria for the evaluation of solutions and the solutions require justification by the solver. The problems are also inter-disciplinary and contain domain characteristics from economics, statistics, management, and decision making. The problem summaries follow.

1. Restaurant: you are district manager of a chain of 32 seafood restaurants. The chain has been evaluating manager performance based on the sales. In order to reduce the chances of discrimination charges, device a plan to evaluate the restaurant's performance based on data provided regarding the location, number of highways, population density, etc.
2. School: as a consultant to a school board, suggest a plan to evaluate principals for merit pay. Data available are the school size (numbers of students), and cost of operating the school.

The problems were presented on a standard 8 × 11 page printed format describing the scenario. Quantitative data was available in ASCII text format, SPSS, SYSTAT, or Excel Formats for each problem. The data were coded as columns representing quantitative information that may or may not aid in the problem solving process. These data were also made available on a laptop loaded with Excel, Systat, and SPSS applications.

Instructions to the participants were included in the problem statement and no further instructions were given. Participants were prompted if the researcher found a slowing of the verbalization.

Even though the problems were ill-structured, to reduce the effects on the outcomes based on the differences in the particular problems, the order of the two problems solved was switched for 10 randomly assigned participants. Group 1 (10 subjects) solved the school problem without-tool followed by restaurant problem with-tool. Group 2 (10 subjects) solved the restaurant problem without-tool followed by school problem with-tool.

2.6. Procedure

The data collection for the study was conducted over a 3-week period. Individual experts were scheduled for three 1-h blocks of time separated by at least a day. All participants received the same materials but the order of presentation was different for half the participants (as described earlier). The first problem was solved without the tool and the second was solved with a tool. The following outlines the format for each session.

2.7. Session one

Subjects were given a brief overview of the procedure and completed the informed consent form and the pre-experiment questionnaire. The researcher also asked questions from the pre-experiment interview. Prior to beginning the problem-solving sessions, a sample think-aloud process was presented to familiarize participants with thinking aloud as they perform problem-solving tasks. Participants practiced the process of verbalizing their thoughts as they solve problems.

The sample think aloud was adapted from Ericsson & Simon (1999). Participants were told: "In this experiment we are interested in what you are thinking and saying to yourself when you perform some tasks. We will give you two problems to solve and you must talk aloud everything that you are thinking and doing while solving the problem. What I mean by talk aloud is that I want you to say out loud everything that you say to yourself silently. Just act as if you are alone in the room speaking to yourself. If you are silent for any length of time I will remind you to keep talking aloud. Before beginning the experiment we will start with a sample exercise.

So talk aloud while you multiply 24 times 34.

How would you advise a student on making a career choice?"

After a short 5-min break, the participant was given the first problem. The problem was school or restaurant. After they read the question, the audiotape was turned on and participants solved the problem. There was no tool present at this session. The researcher only prompted the participant when there was a long silence or when they asked questions on the problem description.

2.8. Session two

After at least 24 h had elapsed since the first session, the second session was scheduled. The researcher presented an overview of the data available using Excel, SYSTAT, or SPSS. Participants were presented the second problem (school or restaurant) and solved the problem with the tool. The problem assignment depended on the first problem solved. If the first problem was school the second was restaurant. If the first problem was restaurant the second was school. The session was also audiotaped.

2.9. Session three

Finally, the post-experiment interview with the subject was conducted and audiotaped.

3. Results

A multivariate analysis of variance (MANOVA) comparing the without-tool and with-tool protocol lengths showed no significant differences for tool presence ($F(3,16) = 3.04$, $p > 0.05$). The use of tools did not significantly increase the length of the problem solution process.

Results from the quantitative and qualitative analysis of data about each research question is described next.

Research Question 1. How are long-term statistical analysis tool experiences (*effect of*) blended with domain knowledge in experts' knowledge structures?

Research Question 2. How are the functions and roles of the statistical analysis tool conceptualized by experts?

3.1. Effect of tool use

To answer the research question on the *effect of* statistical analysis tool use, interview findings, questionnaire summary, and qualitative analysis of think-aloud protocols were used. The interview findings show how experts conceptualized the role of statistical analysis tools. The questionnaire summary highlighted the experiences of the experts. In order to see how their conceptualization of tools affected the experts' representation of ill-structured problems a qualitative analysis of think-aloud protocols was used.

The questionnaire administered before the problem-solving activities asked questions related to years of experience, particular computer software packages used, particular functions within the packages used, and finally familiarity with small case examples similar to those used in this study. All experts had computer experience of more than 2 years. This was confirmed during the interview when all experts suggested that they have used some form of computer tool during their entire professional careers. All experts had used word processing packages, spreadsheets, and internet search engines. Two experts said they had not used specific statistical analysis packages like SPSS or SYSTAT but used Excel to perform similar functions or have their own programs to do them. All other experts had used one of the packages, SPSS, SYSTAT or SAS.

On the specific functions of software packages, 17 of the experts had experience in running regressions and correlations within the past year. Eighteen of the experts had created graphs in the past year. When asked if they had used the functions prior to the last year, all experts said they had used some functions in the past 3 years.

During the initial interview, all experts suggested some or all of the following methods in problem solving: they try to collect data, identify all the possible problem factors and solutions, gauge whether they are able to solve it themselves or have to seek assistance, see what consequences of action or inaction would result in, and try to figure out the best possible answers to their problems. Expert #11 suggested that he uses a "domain knowledge filter" to identify the critical issues in the problem and then follows that with the use of a tool to justify the approach. All experts also suggested the use of previous examples and preferred problem solving patterns when faced with new problems to solve.

The *effect of* tool in the experts in this study showed that the tool skills were interspersed with the domain knowledge. However, the domain knowledge always dictated the problem solving pattern and was present at a higher level in the problem solving network diagram. Fig. 2 shows an example of this pattern.

3.2. Tool conceptualization

On the conceptualization of computer tools, the experts ranged from Expert #11 who suggested that the tool was an "extension of my brain" to others who suggested that they use the tool only when they have all their domain related information

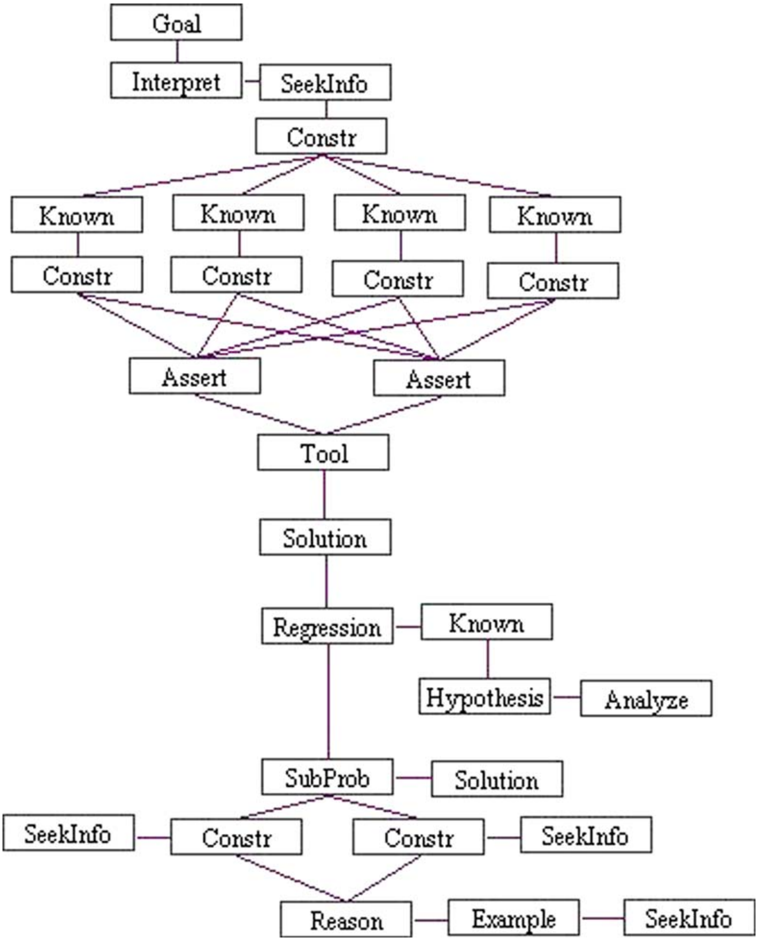

Fig. 2. Expert #20 restaurant problem without-tool.

gathered into a "model" (Expert #12) and then can allow the tool to do analysis that would otherwise be impossible to do by hand. All experts suggested that the tool serves an off-loading purpose to conduct tests, analyze, and visualize data. The daily tool users (8) considered the tool an integral part of their professional activities, and would not consider trying to solve problems without using the tool as a mechanism to bounce ideas off and see if any new problem factors emerge from the tool related function use. These were evident in the statements such as "I look to see if the regression or correlation is a very good fit before deciding if I should identify any alternatives" (Expert #18).

Experts also expected the tool to aid in problem solving by finding nuances in the data and output from tool functions that may be considered affordances to the problem-solving task. For example Expert #11 suggests "I would be very frustrated to not have these tools available to solve the problem. If I saw a fresh problem for the first time, I always run to the tools, and start exploring the data visually and analytically".

The experts also felt very comfortable using the tool to develop arguments in favor of their positions on problems and solutions. For example, Expert #11 suggested that "creating scatter plots of the variables helps decide which types of analysis may be used. After this the regression will tell me what percentage of the variation of the dependent variables is explained by the model. Based on this I can say with confidence whether I can suggest a solution based on the statistics". Similar sentiments were expressed by several other experts, suggesting that tools can be used to justify their solutions.

During the final interview, the experts were asked if they would have conceptualized problems differently if tools were present during the first problem think-aloud session. Twelve of the experts suggested they might have done more analysis if a tool was present (60%). For example, Expert #8 suggested that "there were quite a few variables in the restaurant problem that may have been used to explain the sales, if I had a statistical analysis package I probably could have come up with a model that could predict sales". Six of the experts (60%) who solved the school problem without the tool ($N = 10$) suggested that they really did not believe a tool would have helped too much because they believed so strongly about the qualitative issues associated with schools and those issues were hard to measure with quantitative data. For example, Expert #3, suggested that schools were charged with intellectual development and that could not be measured in quantitative factors, monetary factors, and short-term returns on investments approach. Three of the daily tool users (15%) suggested that they may have identified new constraints to problems if given more time to think about the problems.

The think-aloud protocols provided a similar pattern of responses. The protocols from experts #17, #18, #10, #13, #14, and #2 suggested tool use even when the tool was not present. All of these protocols showed a similar pattern of interpreting the problem, identifying known factors, identifying new constraints, providing domain related reasons, and then proceeding with the tool functions. These experts were quite specific in the functions to be used (i.e., regression), expected outcomes (i.e., predicting sales based on the known factors), and how these could be used in the solution (i.e., reward sales higher than predicted values). An exemplary protocol is shown in Fig. 2. It exemplifies the reliance of tools even when none were present during the problem solving session. This expert's problem representation was also similar to those of other expert's who were daily tool users. Expert #20, a daily tool user, proceeds with the restaurant problem representation even without a tool being present as if he had the tool right in front of him. He thinks completely in line with the processes associated with the tool use and proceeds through all the steps of experts who used the tool. For example "What I would do is run an ordinary least squares regression analysis using sales as the left hand variable. Using those 5 right hand side variables you have there." He even suggested how he would handle different situations that may arise based on output expected from the tool use. For example "forecast what sales would be given this data, and then perhaps you could determine how each manager diverged from their forecasted sales".

The tool functions were also suggested in the context of providing argumentation in favor of a suggested solution. For example, the tool mention was immediately preceding or after a solution alternative was discussed. Economics Expert #17 suggests estimating a statistical model using cost and school size to see if the principal of the school should be rewarded with a merit pay increase.

Finally, while all experts suggested the domain related principles or theories that they were using as a guide to solving the problems, economics expert #17 classified the restaurant problem very early in the problem solving process as a "multivariate regression type problem". This is in contrast to other experts suggesting that the problem was a "managerial performance" or "sales" related problem.

In summary, the *effect of* long-term statistical analysis tool use was observed using a qualitative analysis of think-aloud problem solving by experts. Fig. 2 shows the protocols the best depict this scenario. It appeared that the tool mention came after domain related assertions and principles were discussed in the think-aloud. It is notable that these think-aloud sessions were conducted without the tool and still showed the experts' reliance on the tool. The next section compares the think-aloud without the tool against think-aloud created with the tool to study differences in the *effect with* statistical analysis tools.

Research Question 3. How do domain experts with long-term statistical analysis tool use represent ill-structured problems in the presence of statistical analysis tools (*effect with*)?

Research Question 4. How do domain experts with long-term computer tool use represent ill-structured problems without computer tools?

Research Question 5. Is there a difference in experts' representation of ill-structured problems with and without statistical analysis tools (affordances)?

3.3. *Effect with statistical analysis tools*

This section summarizes statistical and qualitative analysis of think-aloud protocols to identify the *effects with* statistical analysis tools. The statistical tests use numerical weights (one for each mention of the factor associated with problem representation, tool analysis, solutions, and domain knowledge) assigned to verbal protocols collected and a 2×2 multivariate analysis of variance (MANOVA) was performed on the dependent measures. The dependent measures were grouped into conceptually similar functions and are problem space factors (known factors, new constraints identified, interpreting problem), domain knowledge (assertion, reason), tool analysis (hypothesis testing, analysis, tool function, data transformation, visualization), and solution (solution alternative, solution argument).

Qualitative analysis of the protocols identified patterns in problem solving with- and without-tools. Each protocol was graphed using the same protocol codes used earlier. For example, when the verbal segments were coded as visualize and hypothesis testing, then the same codes were used to draw two nodes in the graph. The nodes that were adjacent to each other in the sequence of protocols were connected with a link.

Two qualitative comparisons were made using four examples. First, the school problem without-tool and with-tool were compared for order and relative positions of tool functions as well as domain related information. Second, the restaurant problem without-tool and with-tool were compared on a similar scale.

3.4. Problem representation

The first area of concern for the *effect with* statistical analysis tools was the differences in problem space factors in the with- and without-tools think-aloud problem solving conditions. The measures associated with problem space factors include the known problem factors, new constraints, seeking information, sub problems, and interpreting problem statement. The descriptive statistics for these dependent measures are summarized in Table 2. The results show a higher mean in the without-tool condition for the numbers of new constraints identified and information sought.

The MANOVA indicated a significant main effect for tool presence in problem representation factors (F (5,15) = 6.47, $p < 0.005$) and consisted of the following measures: new problem constraints identified, known problem factors, sub problems identified, interpreting problem, and seeking more information. The univariate tests for each measure are reported in Table 3.

Figs. 3–7 show the without-tool condition resulted in significantly higher frequencies for new problem constraints identified and seeking information. This provides partial support for the *effect with* tool in the form of affordances – constraining and dictating the possible activities performed by problem solvers.

In summary, the problem representation factors were compared in the with- and without-tool conditions. The number of new constraints identified and information sought was significantly higher ($p < 0.05$) in the without-tool condition.

3.5. Domain knowledge

The second area of concern for the *effect with* tools was the mention of domain related knowledge in think-aloud problem solving. The measures associated with domain knowledge include domain related assertions, reasoning, and examples. The descriptive statistics for these dependent measures are summarized in Table 4. The results show a higher mean in domain assertions and reasons in the with-tool condition.

Table 2
Descriptive statistics for the problem representation factor measures

Variable	(N = 20)	
	Mean	SD
Problem 1 – without-tool		
Known probl.	2.10	2.55
New constr.	4.80	3.29
Seek info.	3.70	2.85
Interpret	1.25	0.79
Subproblems	1.70	1.30
Problem 2 – with-tool		
Known probl.	1.75	1.77
New constr.	1.40	2.19
Seek info.	1.25	1.62
Interpret	1.85	1.39
Subproblems	1.40	1.19

Table 3
Summary table of univariate tests for problem representation

Dependent variable	df	MS	*F*	Significance
Within subjects				
New probl. constraints	1	115.60	15.53	0.001
Known probl. factors	1	1.23	0.18	0.674
Sub probl.	1	0.90	0.52	0.481
Interpret probl.	1	3.60	2.69	0.117
Seek more info.	1	60.03	13.34	0.002

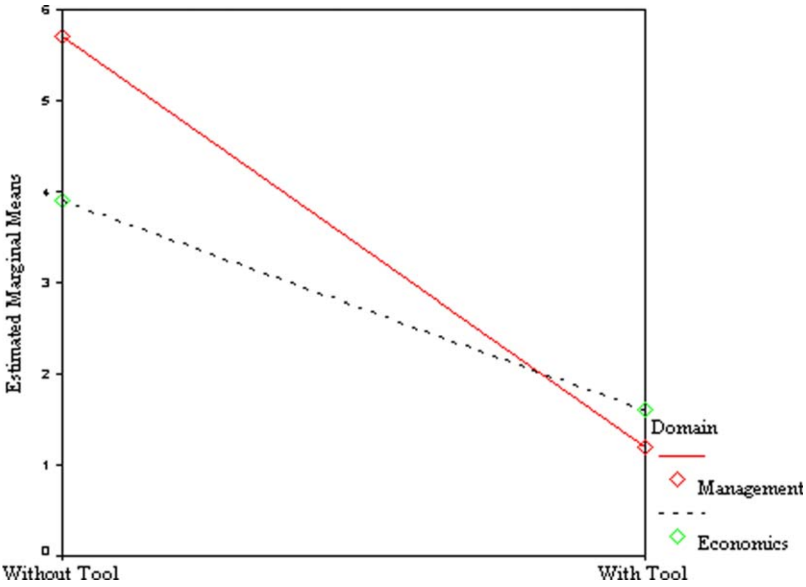

Fig. 3. New constraints by domain and tool presence.

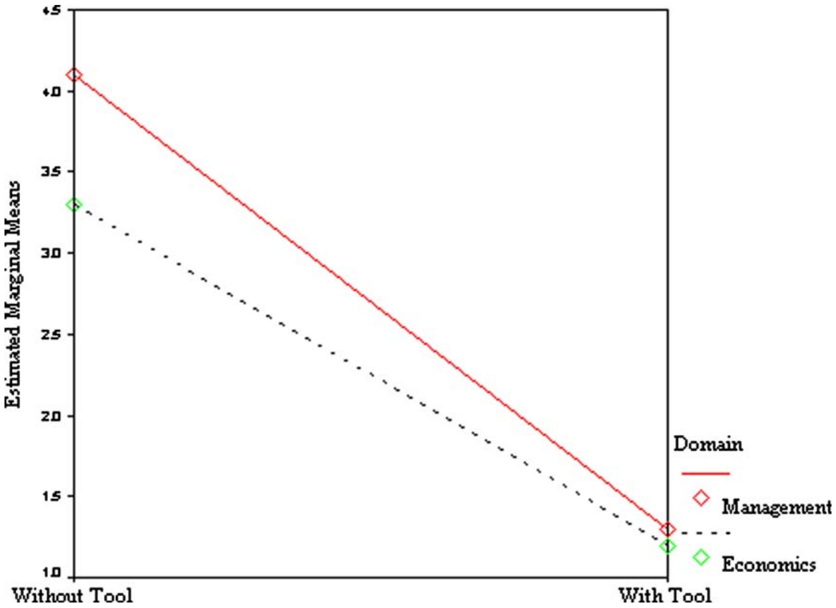

Fig. 4. Seek information by domain and tool presence.

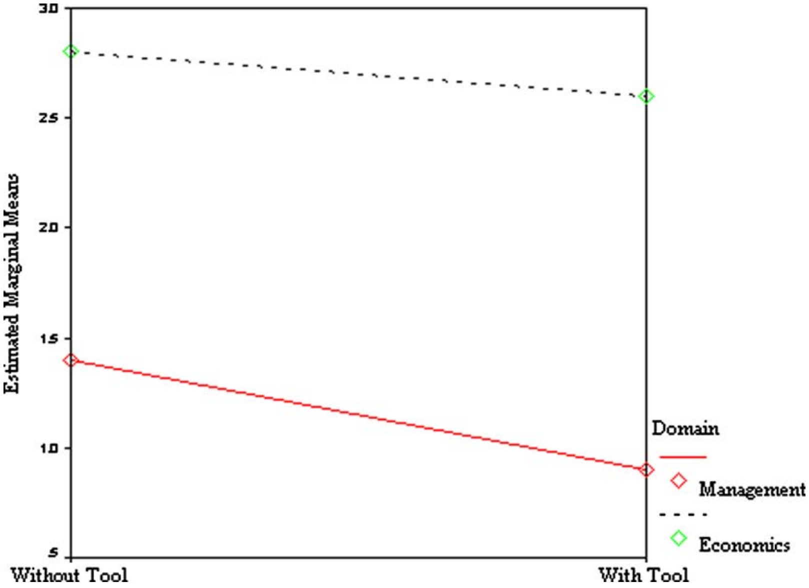

Fig. 5. Known factors by domain and tool presence.

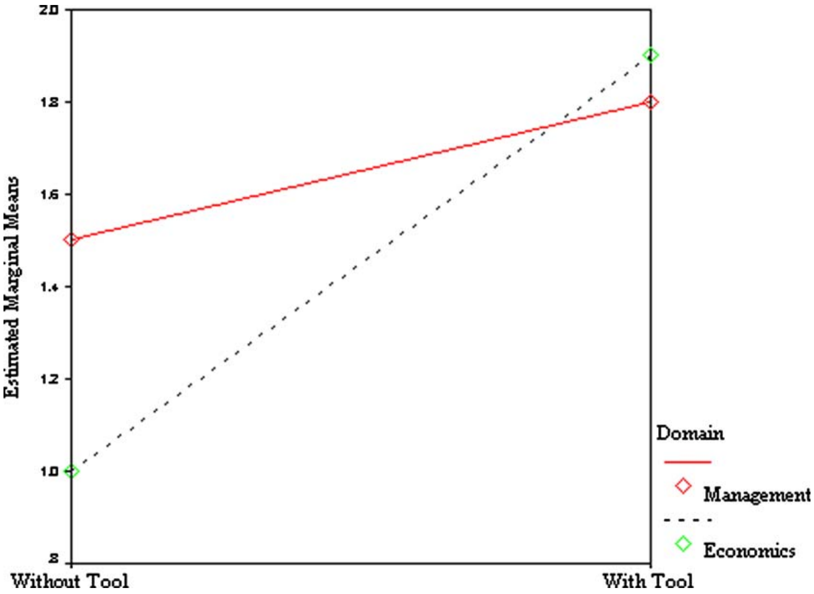

Fig. 6. Interpreting problem statement by domain and tool presence.

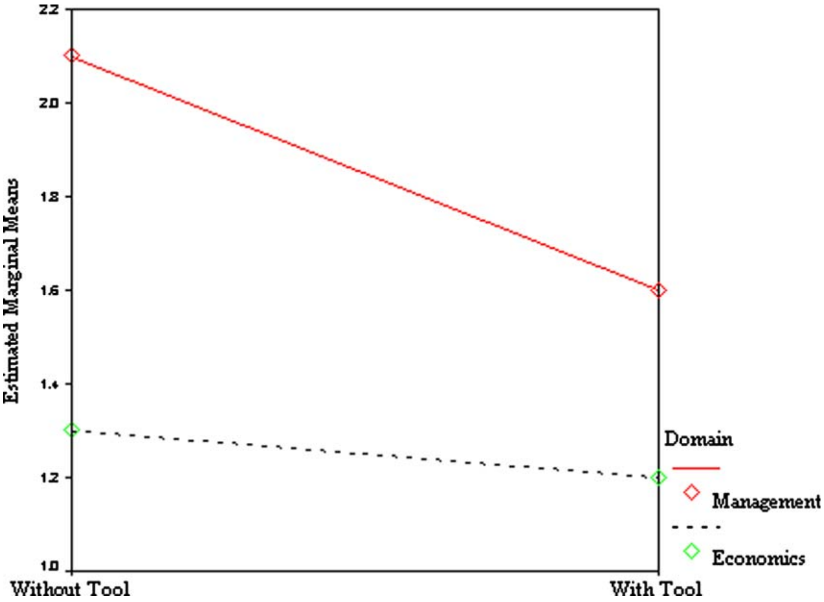

Fig. 7. Sub problems identified by domain and tool presence.

Table 4
Descriptive statistics for the domain knowledge measures

Variable	($N = 20$)	
	Mean	SD
Problem 1 – without-tool		
Domain assertion	1.95	2.56
Domain reason	3.25	2.61
Examples	1.00	1.03
Problem 2 – with-tool		
Domain assertion	3.75	2.45
Domain reason	5.30	3.79
Examples	0.95	1.19

Table 5
Summary table of univariate tests for domain knowledge measures

Dependent variable	df	MS	*F*	Significance
Within subjects				
Domain assertion	1	32.40	5.83	0.026
Domain reason	1	42.03	5.60	0.029
Examples	1	0.02	0.22	0.883

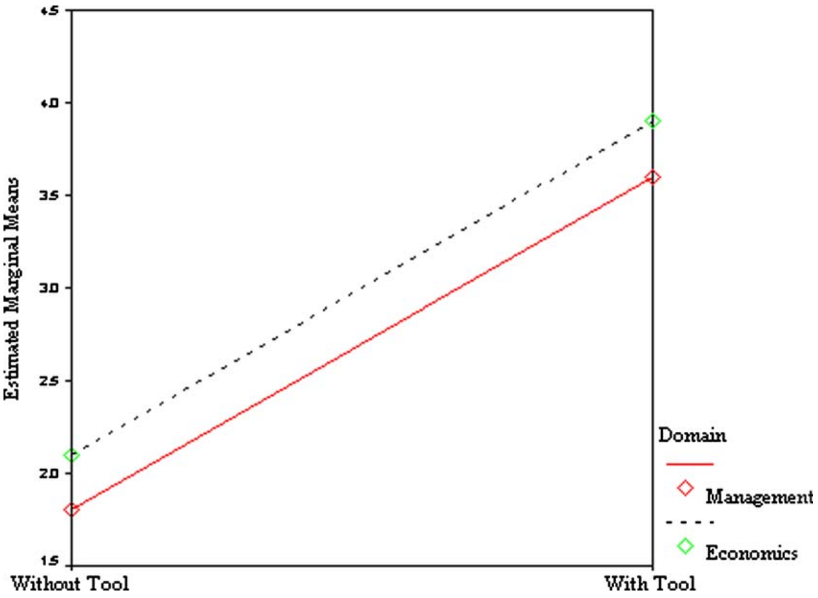

Fig. 8. Domain assertions by domain and tool presence.

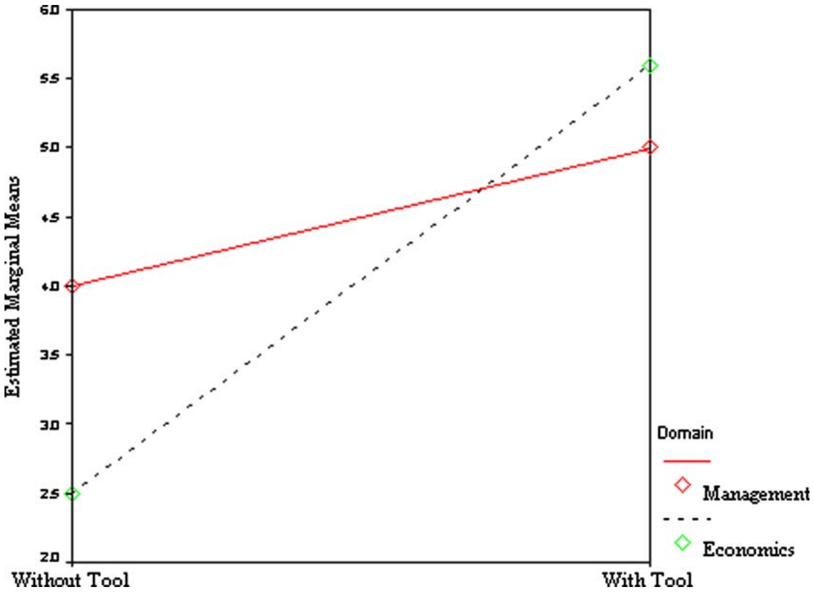

Fig. 9. Domain reasoning by domain and tool presence.

The MANOVA indicated no significant effects for tool presence (F (3,17) = 3.18, $p > 0.05$) and consisted of the following measures: domain assertion, domain reasoning, and examples. Table 5 presents the results from the univariate tests on each measure.

Figs. 8 and 9 show the without-tool condition resulted in higher frequencies for domain assertions and reasoning even though the multivariate tests did not show significant results. This also lends support to the *effect with* tool showing that the presence of tool would affect the problem solving by constraining and dictating the possible activities performed by problem solvers.

In summary, the domain related assertions and reasoning was higher in the with-tool condition of the think-aloud. The numbers of examples were not different between the conditions.

3.6. Tool analysis

A third area of comparison for the *effect with* statistical analysis tools was the tool related activities and analysis of the problem and data. The measures associated with-tool analysis include the testing hypothesis, transforming data, analysis of the output or data, visualizing, and functions. The descriptive statistics for these dependent measures are summarized in Table 6.

The MANOVA indicated significant main effects for tool presence in tool analysis (F (5,15) = 22.29, $p < 0.001$) and consisted of the following measures: visualize data, transform data, analysis, testing hypothesis, and tool functions. Table 7 presents the univariate test results for these measures.

Table 6
Descriptive statistics for the tool analysis measures

Variable	($N = 20$)	
	Mean	SD
Problem 1 – without-tool		
Test hypothesis	0.15	0.37
Analysis	0.45	0.89
Tool function	0.15	0.37
Visualize	0.40	0.60
Transform	0.35	0.75
Problem 2 – with-tool		
Test hypothesis	2.10	2.25
Analysis	6.15	4.59
Tool function	0.55	1.05
Visualize	2.30	1.08
Transform	1.10	1.37

Table 7
Summary table of univariate tests for tool analysis measures

Dependent variable	df	MS	*F*	Significance
Within subjects				
Visualize data	1	36.10	49.35	0.000
Transform data	1	5.63	4.67	0.044
Analysis	1	324.90	33.71	0.000
Testing hypothesis	1	38.03	14.60	0.001
Tool functions	1	1.6	2.27	0.148

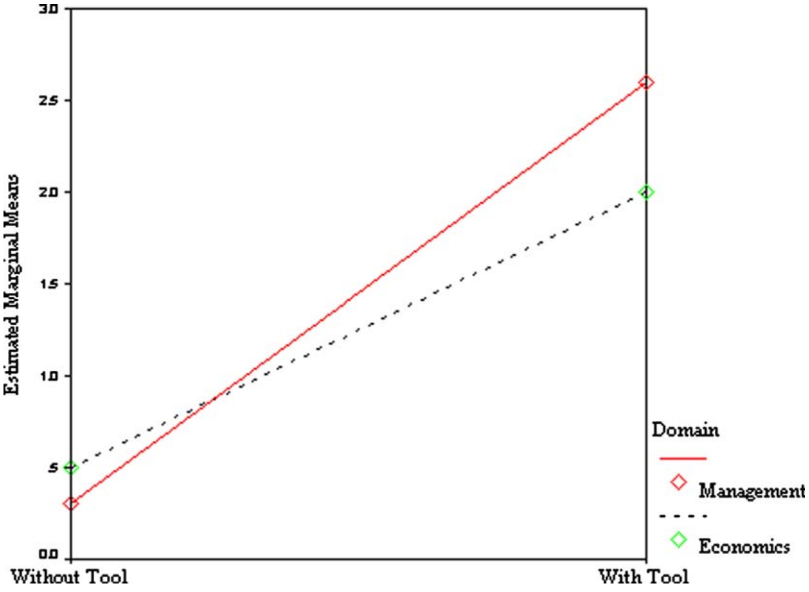

Fig. 10. Visualize data by domain and tool presence.

Figs. 10–13 shows the with-tool condition resulted in significantly higher frequencies for visualizing data, transforming data, analysis, and testing hypothesis. This provides partial evidence that the presence of tool would enhance the effectiveness of the problem solver in functions related to off-load some mental activities (visualizing) and allow more hypothesis testing. If more hypotheses are tested then the analyses must follow and therefore the analysis variable also was significantly higher in the with-tool condition.

In summary, tool analysis was compared in the with- and without-tool think-aloud problem solving conditions. The statistical tests show that the tool presence resulted in higher hypothesis testing, analysis, transformation of data, and visualization.

3.7. Solution(s)

The fourth and final area of comparison for the *effect with* statistical analysis tools is the number of solutions proposed and arguments in support of the solutions. The solution measures included the number of alternatives considered as well as the arguments in favor of the alternatives. The descriptive statistics for these dependent measures are summarized in Table 8.

The MANOVA indicated no significant effects for tool presence in solution ($F\,(2,18) = 2.25$, $p > 0.05$) and consisted of the following measures: solution alternative and solution argument. Table 9 present the univariate test results for the solution measures.

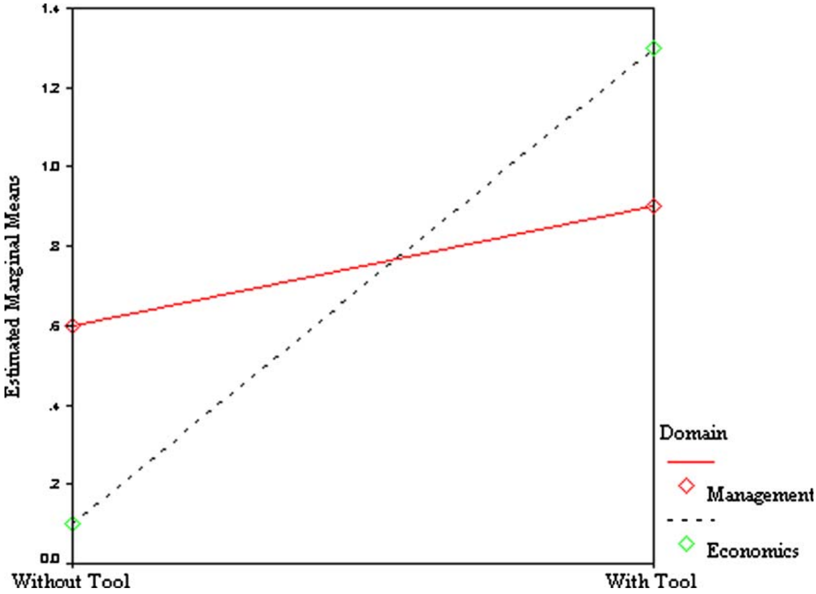

Fig. 11. Transform data by domain and tool presence.

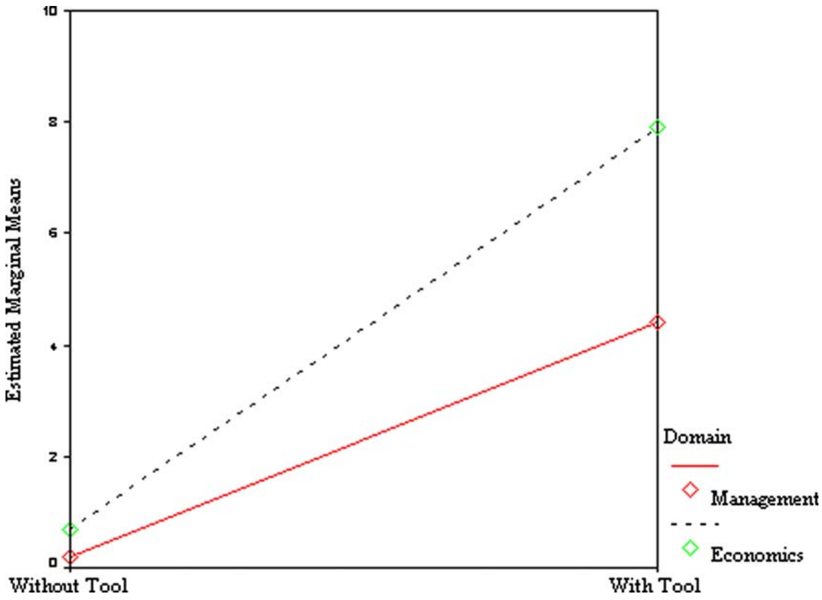

Fig. 12. Analyze data by domain and tool presence.

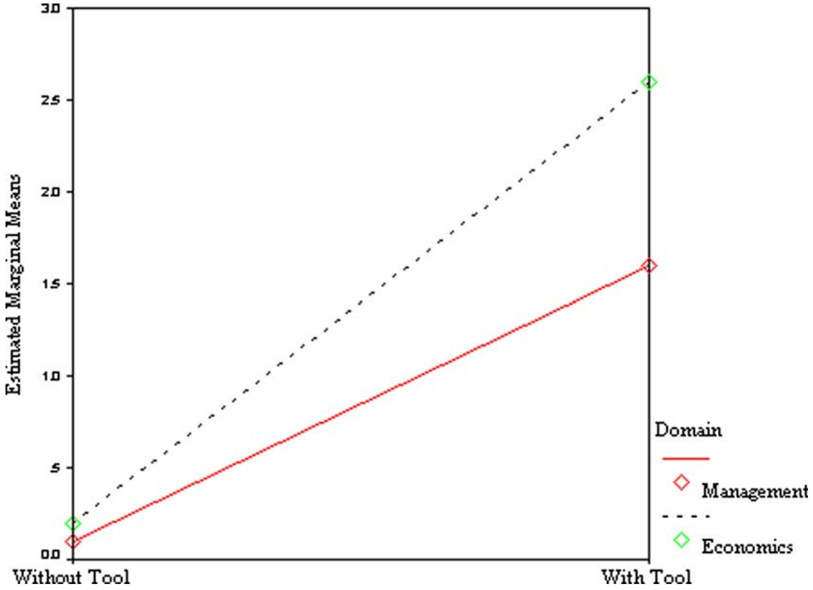

Fig. 13. Test hypothesis by domain and tool presence.

Table 8
Descriptive statistics for the solution measures

Variable	($N = 20$)	
	Mean	SD
Problem 1 – without-tool		
Alternative	2.30	1.26
Argument	2.15	1.46
Problem 2 – with-tool		
Alternative	2.30	1.59
Argument	3.15	2.39

Table 9
Summary table of univariate tests for solution measures

Dependent variable	df	MS	*F*	Significance
Within subjects				
Solution alternative	1	0.00	0.00	1.000
Solution argument	1	10.00	1.96	0.178

There were no significant differences in the number of solution alternatives considered and the number of arguments in favor of the solutions between the with- and without-tool conditions.

3.8. Qualitative comparisons documenting effect with

In order to document the effect with statistical analysis tools, two qualitative comparisons use the transcribed and coded protocols to highlight some of the findings related to order of presentation and approach to the problem. The first comparison presented here shows the school problem with- and without-tool. The second comparison shows the restaurant problem with- and without-tool.

3.9. School problem

The School problem was based on data on 16 schools within a school district and the principal requesting a merit pay raise based on the lowest cost for operating the school. The factors contributing to the analysis can vary ranging from quality related issues (student performance), morale related issues (teachers, staff, and community), as well as the cost factor identified by the principal seeking the raise. The underlying theoretical basis identified by all the experts was "Economies of Scale" in running larger schools. This theory suggests that when fixed costs (physical plant) are high, as the school size gets larger the average cost gets smaller.

Two examples were picked because they exemplify the expert's representation of ill-structured problems with- and without-tools. In order to highlight the significant differences of conceptualizing problems with- and without-tools examples of expert protocols were picked based on whether they approached the problem using techniques and steps described by previous researchers (Voss et al., 1983) and ill-structured problem solving methods (Jonassen, 1997). For the without-tool example protocol these included the number of new constraints identified, contextual factors, multiple perspectives to the problem and an approach that reflected the ill-structured nature of the problem. For the with-tool condition, the effectiveness of tool use and its use to narrow the focus of the problem was the criteria for selection. The following examples show how management expert #21 approached the school problem (without a tool) as a complex set of factors and constraints affecting the choices and economics expert #20 approaching the same school problem using a statistical analysis tool and almost converting the ill-structured problem into a well-structured single answer type problem. The detail descriptions follow.

3.10. School problem without-tool – management expert #21

As shown in Fig. 16, the participant started with the goal and quickly proceeded to give domain related reasons for interpretations and solution alternative. For example "I notice the key thing here is that her request is based on how efficient she is. And I think that is a very nebulous, not necessarily nebulous but a singular measure for if she is doing a good job." He proceeds to suggesting that efficiency does not imply effectiveness and then suggests that other factors must be considered. Based on this reasoning the participant then proceeded to identify four new constraints (type of school must be found, SAT scores, college acceptance rates, and type of community) to the problem and sought more information regarding each constraint in order to solve the problem. He suggests that he may be able to come up with whether the principal is deserving of a merit pay raise but cautions that "the basis of having the cheapest school in town, scares me a bit". Justifying this statement by using "economies of scale" the domain related theory.

Finally, another constraint regarding how costs were calculated is identified. Based on examples of different forms of calculating costs a new sub problem is identified.

Similar to this representation of the school problem without the tool, economics experts #16, #19, management experts #8, #1, #4 identified at least four new constraints to the problems and sought more information to solve the problem. Some examples of constraints included the "types of programs offered by the school" (expert #16), "Other administrators may be helping to create the cost savings, maybe a team merit pay should be considered" (expert #8), "Are the parents happy with the school" (expert #8). Fig. 14 shows portions of protocols to highlight the similarities.

The solutions proposed by these experts also revolved around seeking more information and were not directly tied to the request from the principal for a merit pay raise. For example, expert #8, suggests that "I will tell the school board to get more data" before providing a final solution. Expert #1 also suggested that solutions may be proposed only after more information is analyzed. see Fig. 15.

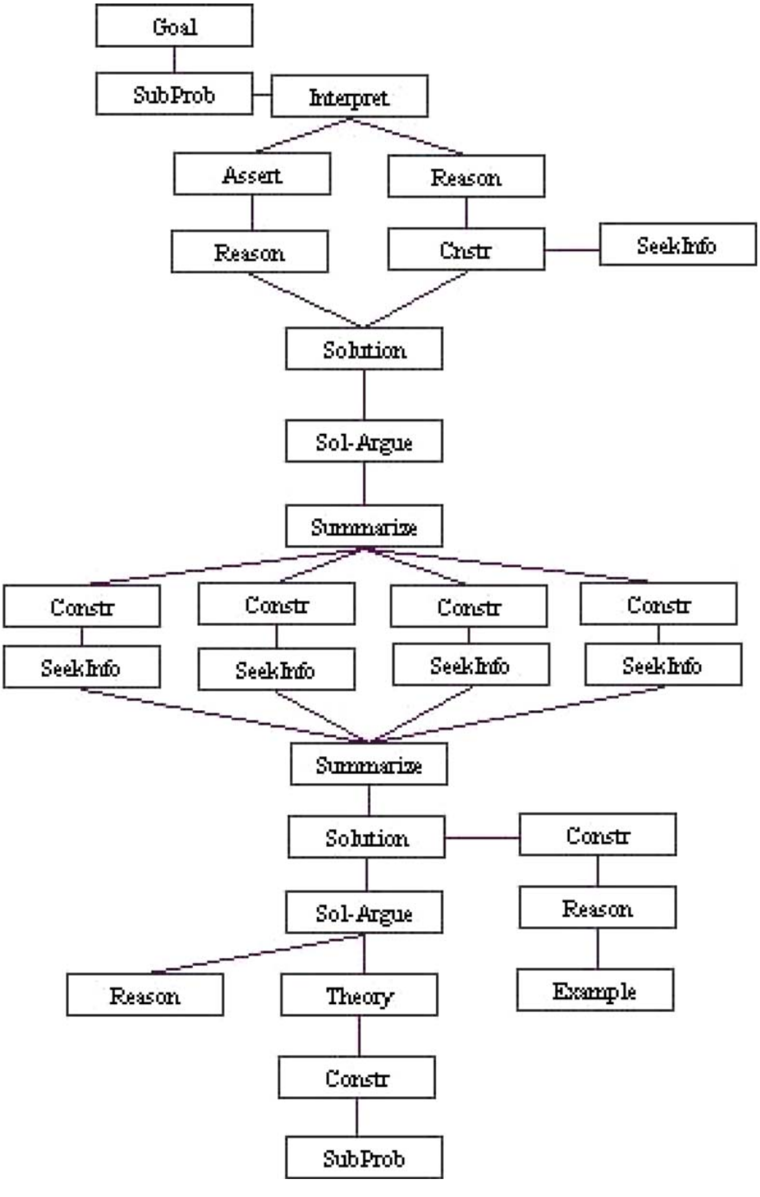

Fig. 14. School problem without-tool expert #21.

3.11. School problem with-tool – economics expert # 20

On the other end of the spectrum, the same school problem conceptualized with a tool shows the expert starting with an interpretation of the problem statement and quickly proceeding to domain related assertions and testing hypothesis

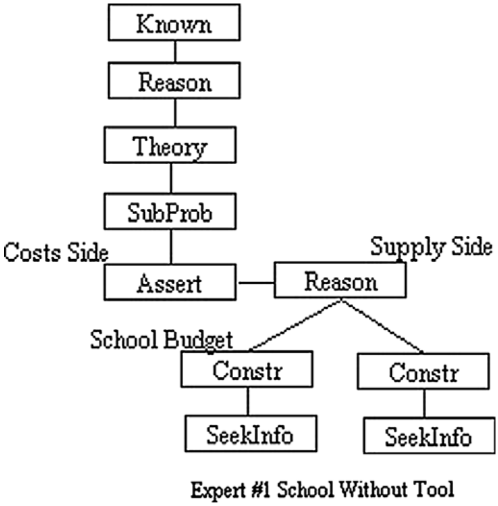

Fig. 15. Other protocols showing similar patterns.

(Fig. 16). For example he starts by zeroing in on the statement "Request to analyze the data" following by an interpretation "this principal has asked for a raise and says that per pupil cost is lowest among schools". The follow up to this statement is asserting that "she also has the biggest school" and theory and reasons in the form of "average costs may be decreasing as school size gets large". He then followed up with transformations to the data (off-loading) (i.e., creating another column with total cost) and giving domain related reasons for each step and conducting a regression analysis. He discussed the findings from this analysis and gave domain related reasons for the findings. He visualized (off-loading) the data and explains the findings again. He also gives a narrowly focused answer that may be considered more suitable to a well-structured problem than an ill-structured problem affected by many factors.

Similar patterns were observed in management experts #3, #8, #9, #10, and economics experts #13, #14, #15, and #18. While these experts did suggest some additional new constraints they all used the tool to suggest that the principal was not deserving of the raise based on the statistical tests. Management expert #5 was the only person who suggested that she would not use the tool because she felt very strongly that the efficiency factor should be least useful for a merit pay raise.

3.12. Comparing representations of the school problem with- and without-tools

The comparison between the two diagrams shows differences in approaches from many aspects. First, the without-tool condition had the experts conceptualizing the problem broadly and including many external constraints (ranging from 4 to 11) and explaining the reasons for Dr. Griedy's performance using the theory of "Economies of Scale". When conceptualizing the problem with the tool economics expert #20

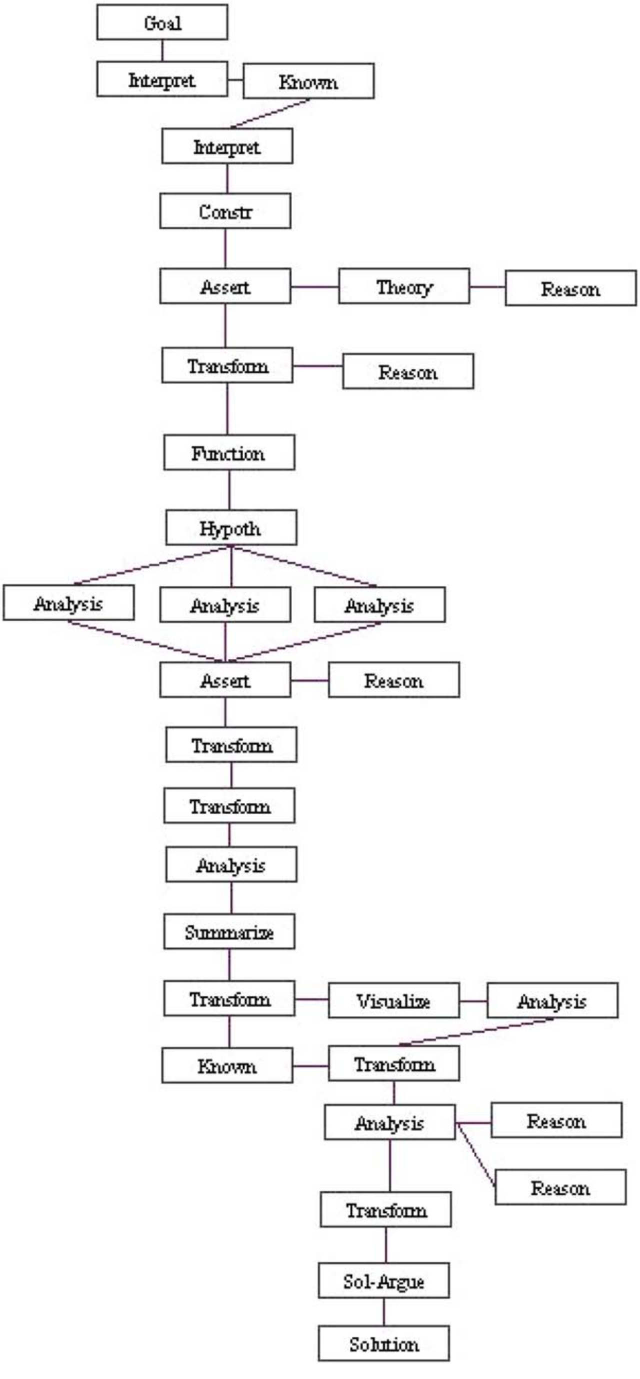

Fig. 16. Economics expert #20 – school problem with-tool.

and others (management experts #3, #8, #9, #10, and economics experts #13, #14, #15, and #18) performed statistical tests to prove or disprove the case that the principal was making and were not inclined to seek a broader perspective. The presence of the tool appeared to narrow the focus of the problem but allowed interactions between the tool and expert in the form of testing hypothesis, transforming data, and visualizing information. Evidence of hypothesis testing include, expert #20, "so the first thing I would look at is that average cost may be decreasing as school size gets large as there may be some fixed costs that are spread over a larger and larger amount of students". Data transformations include, "I am going to create another column, … divide the total cost by the number of students". Visualizing the information can be seen in "by sorting it (the cells) I can see where she ends up". Expert #10 graphed the fixed and variables costs to see where the principal's school fell in the district.

3.13. Restaurant problem

The restaurant problem was based on management principles of performance appraisals, incentives, and rewards. The data provided to the experts included some demographic information and sales. Additional constraints included the profit margin, more customer oriented demographics like age, and customer service issues like return visits, average check size. Another twist to the problem included the gender of the managers and the group of females that are threatening to sue if fired. The representation of this problem was also similar to the previous comparison with experts identifying more external constraints in the without-tool condition than the with-tool condition.

3.14. Comparing the restaurant problem representations with- and without-tools

Similar to the comparisons made earlier using the school problem, the restaurant problem also showed experts conceptualizing problem differently in the presence of a tool. There was increased hypothesis testing, visualization, analysis, and data transformation in the with-tool condition. The tool functions were also immediately preceding or after the solutions and used as justification for the proposed solutions. In the without-tool condition, there were higher frequencies of new constraints identified and information sought.

3.15. Summary – patterns in experts' representation of ill-structured problems

The following steps were identified as common themes to the experts' representation of the chosen ill-structured problems *without-tools*.

1. Identifying goal(s) from problem statement.
2. Interpreting the problem statement according to what they perceive as important.

3. Identifying domain related theories that may explain the problem.
4. Identifying factors given in the problem statement that may be useful to the solution process.
5. Identifying other constraints to the problem not given in the problem statement.
6. Presenting alternative perspectives to the problem with examples.
7. Identifying solution alternatives.
8. Evaluating the alternatives.
9. Suggesting a solution and justifying it.

When experts *used statistical analysis tools* this process was intertwined with-tool functions, approaches, analysis, and testing hypothesis.

1. Identifying goal(s) from problem statement.
2. Interpreting the problem statement according to what they perceive as important, using tool functions to re-order the data, visualize and create descriptive statistics of the data provided.
3. Identifying domain related theories that may explain the problem, identifying tool functions that may be useful.
4. Identifying factors given in the problem statement that may be useful to the solution process, suggesting the impact of these factors, testing these hypothesis.
5. Identifying other constraints to the problem not given in the problem statement (very limited).
6. Presenting alternative perspectives to the problem with examples (very limited).
7. Identifying solution alternatives based on the tool outcomes and analysis.
8. Evaluating the alternatives using the tool's functions.
9. Suggesting a solution and justifying it using the tool outcomes.

Finally, evidence has been presented to show how experts' conceptualized tool experience, how this *effect of* tool experience influenced think-aloud problem solving. Evidence for the *effect with* tools was presented using quantitative and qualitative comparisons. These *effects with* tools included significantly higher numbers in hypothesis testing, analysis, transformation of data, and visualization measures. The without-tool condition of think-aloud problem solving showed a significantly higher number of new problem constraints identified and information sought.

4. Discussion

The purpose of this study was to first identify the *effects of* long-term computer tool use and second investigate whether there were differences in how experts represented ill-structured problems with- and without-tools. The participants were experts ($N = 20$) (professors and other professional consultants) in the domains of economics ($N = 10$) and management ($N = 10$). These experts had an 18.55 average number of years of domain experience and at least 2 years of experience with statistical analysis tools.

The data for this analysis and discussion come from multiple sources, interviews, questionnaires, think-aloud problem solving with-tool, and think-aloud problem solving without-tool.

Experts' conceptualized statistical analysis tools as extensions of their brains, as tools to off-load mental functions to, and as integral to their problem solving activities. The experts also expected affordances from the tools.

These findings may provide partial evidence of what Salomon (1990) describes as the interaction between tool and human where the program affords or constrains behaviors and the user must accept or take what is provided by the tool. Here, the user appears to be "in charge" of their activities by imposing their domain knowledge and expertise to use the tool to provide assistance to them.

Another form of "being in charge" of the tool use was evident in the statements by some of the experts that they would not use the tool because of the nature of the task. For example, expert #5 suggested, "I will not use the tool because the school related issues are more complex and cannot be measured purely on the efficiency factors". Expert #3 also suggested that "Schools are charged with the intellectual development of a whole person and using efficiency as a factor will not be appropriate". Expert #3 continued by suggesting that the school board could be educated by the consultant to identify their values and beliefs before proceeding with the merit pay review.

In the problem representation, there was evidence of tool experience in the classification of the problem as well as the order to the problem representation. Specifically, it was observed that domain knowledge was used by all the experts in the assertions, reasoning, hypothesis testing, examples, and analysis.

This study finds that 19 of the 20 experts classify problems according to their prior domain knowledge. The classification is evident in the following examples. Expert #4, "This is an Economies of Scale problem". Expert #16, "This is a returns to scale issue". Expert #1, "Economies of scale is the issue here". The classification of the school problem was consistently "Economies of Scale" and the restaurant problem was "manager evaluations/rewards" or "performance incentives".

The classification of the problem using prior domain knowledge supports findings by Chi et al. (1981), Patel and Groen (1986), Voss et al. (1983). Similar to the previous research findings, the experts in the current study "filtered" (economics expert #11) the problem factors through their domain knowledge to identify the critical factors and classify the problem.

After classification of the problem the experts imposed structure to seek information and solve the problem using their pre-determined approach. Examples of this include expert #8 who suggested "This is a classic economies of scale problem" followed by "I would calculate the fixed costs, variable costs" and "draw a graph using the residuals", finally, "you can see as the number of students goes up the cost per student goes down". Expert #17, "I believe the income and density should be positively correlated with the sales" followed by running the correlations and concluding, "you can see that the correlations are high as I had expected them to be".

Patel & Groen (1986) found that experts conducted forward reasoning by hypothesizing what the cause of problems may be and seeking evidence to support their diagnosis. A parallel structure was observed in this study. Here, the experts hypothesized the role of different factors affecting the problem and used the tool to test the hypothesis. For example, each variable provided in the problem statement was weighed based on the domain knowledge of the expert, a hypothesis about what would be expected was stated, and finally the hypothesis was tested and analyzed to see if they were consistent with their expectations. In all instances, the experts' domain knowledge-based hypothesis tested true to their expectations. For example expert #21 suggested, "you obviously have to account for things like income, density of the population, the 4 firm concentration ratio is a very useful measure the problem is we don't know from here where they are within it", he proceeded to test these hypotheses and suggest "the key ones here relate to income of course".

In the order of problem representation the current study finds a pattern of interpreting problem, classifying the problem, using domain knowledge assertions and reasons, identifying known factors, identifying new constraints to problems, seeking information, proposing solutions, and justifying solutions. Expert #21's problem representation highlighted the pattern. Similar patterns were observed by Patel & Groen (1986) & Voss et al. (1983).

This study found two additional elements that were not reported by the existing studies, information seeking and *effect of* tool experience. The tool experience was expected but the information seeking was unexpected.

For information seeking, the current study found that when experts identified new constraints to the problem (i.e., the effectiveness of the principal) then they identified specific factors that may be used to measure the effectiveness and sought information before they would suggest a solution. For example expert #1 suggested, "I would need more information on the local school district, taxes, and other performance related factors before I can give my opinion". Even though Voss et al. (1983) conducted studies using ill-structured problems, the experts in their studies appeared more focused towards generating sub problems and providing an answer than to seek more information.

On the *effect of* tool experience this study has documented how prior experiences with-tools (gathered from the questionnaire) appears to affect the conceptualization of the tool (gathered from the interview) and how this conceptualization affects problem representation (based on the qualitative analysis of think-aloud protocols). The problem representation of the experts in the current study documented that the tool functions are interwoven within the process. However, similar to the findings from previous research 19 of 20 experts followed a pattern of preceding tool mention with domain knowledge assertions, reasons, and hypothesis.

This may provide partial support to the concept of problem schemas suggested by Chi et al. (1981) & Rumelhart (1980). Gick (1986, p. 102) suggest that problem schemas contain a "cluster of knowledge related to a problem type" with abstracted information about the problems as well as some problem specific surface features.

The abstracted categories include relevant underlying principles, concepts, relations, procedures, rules, operations, and facts from the domain (Bernardo, 1994; Voss, 1988), and goals, constraints, and solution procedures associated with the problems (Gick, 1986). This problem schema is then said to aid in how experts classify, seek information, and solve problems (Chi et al., 1981).

Similarly, the current study shows that these experts use their domain knowledge to impose structure (stating hypothesis, domain related assertions, and examples) and filter the problem, test hypothesis, identify new constraints, and propose solutions based on the problem representation.

However, based on the current research showing the intertwining of tool functions among the domain knowledge factors, we may infer that the problem schemas may contain factors associated with-tools. Specifically, tool functions and expectations of output from the tool may be included in problem schema. Expert #20's problem representation contains both tool functions and domain related statements.

A notable exception to the classification and organization of the think-aloud protocol was economics expert #17 who classified the problem as a "regression problem" instead of using any domain related theories or principles. All other experts classified the problems using domain related principles (i.e., economies of scale), assertions, and reasons. While it may be that this exception to the rule happened by chance, it is worth pursing possible causes to this outcome.

In conclusion, this study has shown how domain knowledge and tool skills are intertwined in these experts' problem schemas. The tools have become an integral part of their problem solving process. The presence and absence of tools also appear to influence the problem representation, analysis, solution alternatives, and justification.

Appendix A. Problem 1 – restaurant©

You are district manager of a chain of 32 seafood restaurants. The Red Herring chain has been evaluating store managers by their order of sales. For example, in the last month, managers of stores 22, 25, 28, and 32 were given special recognition and bonuses for their "exceptional performance." The manager of store 28 was given the "King of the Hill" award for excellence in recognition of this $ 200,000 in sales in the benchmark month. Managers of all the other stores were told by the corporate-level sales manager, Atil A. Hunne, that they need to pick up the pace. It was implied that managers of stores 7–17, 27, and 30 might get bad evaluations that could lead to separation from Red Herring. As Hunne put it, "anyone who is not doing $ 100,000 of business is not pulling his weight." Managers 7, 9, 27, and 30 believe that they are doing a good job and have implied that they will enter a comparable worth gender discrimination suit, if fired. Evaluate the attached data to see if there is a better way

---

© Copyright Willard Raddell, Ph.D. Used with Permission.

to evaluate the managers. You have been hired by George A. Batbert, CEO of Red Herring, to evaluate the data and to report on the current evaluation system and propose changes.

Last month's data:

Store#	Sale	Dense	CR4	Income	Gender	Highways
1	139,000	28	20	40,000	1	2
2	125,000	25	30	35,000	1	2
3	120,000	23	40	26,000	1	1
4	110,000	17	45	30,000	0	1
5	105,000	16	50	28,000	1	2
6	100,000	15	45	24,000	1	1
7	90,000	13	53	22,000	0	0
8	80,000	5	88	10,000	1	0
9	75,000	10	65	19,000	0	1
10	70,000	11	60	15,000	1	1
11	60,000	15	35	25,000	1	1
12	49,000	7	55	17,000	1	0
13	46,000	8	85	14,000	1	0
14	40,000	3	95	10,000	1	0
15	95,000	12	50	18,000	0	1
16	30,000	5	90	11,967	1	0
17	35,000	6	88	12,250	1	0
18	165,000	38	20	25,000	0	2
19	150,000	35	16	32,000	1	1
20	175,000	40	12	31,000	0	2
21	135,000	27	46	21,000	0	1
22	180,000	45	20	35,000	1	2
23	175,000	22	17	19,000	0	3
24	150,000	17	28	22,000	0	1
25	190,000	39	8	38,000	1	3
26	85,000	15	55	17,000	1	1
27	50,000	9	45	13,000	0	0
28	200,000	48	14	39,000	1	2
29	150,000	54	80	24,000	1	1
30	80,000	14	90	16,000	0	0
31	100,000	34	60	20,000	1	1
32	190,000	57	30	36,000	0	2

Sales are in dollars; population density is in number of persons per census block in a 5 mile radius of each Red Herring; CR4 is the 4-firm concentration ratio for restaurants in a 5 mile radius of each Red Herring (market share of top four restaurants in each market area); income is per capita within census blocks within a 5 mile radius of each Red Herring; gender of managers is one for male and zero for female; highways is the number of 4-lane divided highways within a 5 mile radius of each Red Herring.

Appendix B. Problem 2 – school©

March 18, 2000
Jan Smith, Director
Pennsylvania MBA Associates
888 Easy Street
Harrisburg, PA 17605
Dear Ms. Smith:

Upper Stork School District 99 Board requests that you consider accepting a contract to analyze a request for a merit pay bonus from one of our principals. Dr. Ima Barry Griedy operates a school with 3100 students at a cost per student of $ 4600. Dr. Griedy has sent a letter which says

> my request for a merit pay bonus of 10% for the next school year is based upon the fact that I have run my school in an extraordinarily efficient manner. With 3100 students in my school, the cost per pupil has been only $ 4600. That means that I manage the most cost-efficient school in the system. While I not like to "toot my own horn", it is clear that cost data show that my school is managed in an efficient manner. A favorable ruling by the Board on my request for merit pay will send a signal to the less efficient school that better performance is possible with proper management. That you for considering my request.

Because of your MBA experience, the School Board has decided to offer you a contract on this request. While the Board is happy to offer you a contract for $ 3000 to complete this study, there are some members of the Board who feel your study will be a waste of money. One Board member said that

> I hope you're not going to hire one of those damned intellectuals with diarrhea on the word processor. I don't read anything that's over one page.

In general, the Board is happy that you were hired, because, although the Board will happily pay a merit bonus if Dr. Griedy has really done better than other principals, Dr. Griedy has a reputation as a fast talker and we do not want to be snookered.

Following are the data for the entire school district:

Per pupil cost school size (pupils in average daily attendance)

$ 9000	400
8000	475
7500	700
6700	750
6600	1100
6100	1100
5600	1300
6000	1350
5800	1500

(*continued on next page*)

5100	1650
5500	1700
5400	2000
4900	2200
5000	2300
4800	2450
4600	3100

On behalf of the Board, I look forward to a mutually productive association. Let us know within 10 days what your proposed solutions are.

Sincerely,
Jack S. Kieper,
Chairman

References

Bernado, A. B. I. (1994). Problem-Specific information and the development of problem-type schemata. *Journal of Experimental Psychology: Learning, memory, and cognition, 20*(2), 379–395.

Canizares, C. A., & Faur, Z. T. (1997). Advantages and disadvantages of using various computer tools in electrical engineering courses. *IEEE Transactions on Education, 40*(3).

Carter, G., Westbrook, S. L., & Thompkins, C. D. (1999). Examining science tools as mediators of students' learning about circuits. *Journal of Research in Science Teaching, 36*(1), 89–105.

Chi, M. T. H. (1997). Quantifying qualitative analyses of verbal data: a practical guide. *The Journal of the Learning Sciences, 6*(3), 271–315.

Chi, M. T. H., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121–152.

de Jong, T., Martin, E., Zmarro, J., Esquembre, F., Swaak, J., & van Joolingen, W. R. (1999). The integration of computer simulations and learning support: an example from the physics domain of collisions. *Journal of Research in Science Teaching, 36*(5), 597–615.

Dixon, J. K. (1997). Computer use and visualization in students' construction of reflection and rotation concepts. *School Science and Mathematics, 97*(7), 352–358.

Ericsson, K. A., Simon, H. A., (1993, 1999). *Protocol analysis: verbal reports as data*. Revised Edition. Cambridge, MA: The MIT Press.

Ericsson, K. A., & Smith, J. (1991). *Toward a general theory of expertise, prospects, and limits*. Cambridge: Cambridge University Press.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton Mifflin.

Gick, M. L. (1986). Problem-solving strategies. *Educational Psychologist, 21*(1 and 2), 99–120.

Heath, C., & Luff, P. (1998). Convergent activities: Line control and passenger information on the London underground. In Y. Engerstrom & D. Middleton (Eds.), *Cognition and communication at work*. Cambridge, UK: Cambridge University Press.

Henning, P. H. (1998). Ways of learning: an ethnographic study of the work and situated learning of a group of refrigeration service technicians. *Journal of Contemporary Ethnography, 27*(1), 85–136.

Hill, J. A., & Hannafin, M. J. (1997). Cognitive strategies and learning from the world wide web. *Educational Technology Research and Development, 45*(4), 37–64.

Hong, N.S., 1998. The relationship between well-structured and ill-strucrured problem solving in multimedia simulation. Unpublished Doctoral Dissertation. The Pennsylvania State University Press.

Hutchins, E. (1995). How a cockpit remembers its speeds. *Cognitive Science, 19*, 265–288.

Hutchins, E., & Klausen, T. (1998). Distributed cognition in an airline cockpit. In Y. Engerstrom & D. Middleton (Eds.), *Cognition and communication at work*. Cambridge, UK: Cambridge University Press.

Jonassen, D. H. (1997). Instructional design for well-structured and ill-structured problems. *Educational Technology Research and Development, 45*(1), 656–694.

Jonassen, D. H. (2000). *Computers as mindtools for schools: Engaging critical thinking* (2nd ed.). Upper Saddle River, NJ: Prentice-Hall.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949–968.

Lesgold, A., Rubinson, H., Feltovich, P., Glaser, R., Klopfer, D., & Wang, Y. (1988). Expertise in a complex skill: diagnosing X-ray pictures. In M. R. H. Chi, R. Glaser, & M. L. Farr (Eds.), *The nature of expertise*. Hillsdale, NJ: Erlbaum.

Lindström, B., Marton, F., Ottosson, T., & Laurillard, D. (1993). Computer simulation as a tool for developing intuitive and conceptual understanding in mechanics. *Computers in Human Behavior, 9*, 263–281.

Mayes, R. L. (1995). The application of a computer algebra system as a tool in college algebra. *School Science and Mathematics, 95*(2), 61–67.

McKeague, C. A. (1996). *Effects of hypertext structure and reading activity on novices' learning from text*. Unpublished Doctoral Dissertation, The Pennsylvania State University.

Morgan, B. B., Jr., Herschler, D. A., Wiener, E. L., & Salas, E. (1993). Implications of automation technology for aircrew coordination and performance. *Human/Technology Interaction in Complex Systems, 6*, 105–136.

National Research Council. (1996). *National science educational standards*. Washinton, DC: National Academy Press.

Norman, D. A. (1988). *The psychology of everyday things*. Basic Books.

Patel, V. L., & Groen, G. K. (1986). Knowledge based solution strategies in medical reasoning. *Cognitive Science, 10*, 91–116.l.

Patel, V. L., & Groen, G. K. (1991). The general and specific nature of medical expertise: a critical look. In K. A. Ericsson & J. Smith (Eds.), *Toward a general theory of expertise: Prospects and limits*. Cambridge: Cambridge University Press.

Pea, R. D. (1985). Beyond amplification: using the computer to reorganize mental functioning. *Educational Psychologist, 20*(4), 167–182.

Pea, R. D. (1993). Practices of distributed intelligence and designs for education. In G. Salomon (Ed.), *Distributed cognitions: Psychological and educational considerations*. Cambridge: Cambridge University Press.

Perkins, D. N. (1985). The fingertip effect: how information-processing technology shapes thinking. *Educational Researcher, 14*(6), 11–17.

Roth, W. M. (1995). Affordances of computers in teacher–student interactions: the case of interactive physics. *Journal of Research in Science Teaching, 32*(4), 329–347.

Roth, W. M., Woszczyna, C., & Smith, G. (1996). Affordances and constraints of computers in science education. *Journal of Research in Science Teaching, 33*(9), 995–1017.

Rumelhart, D. E. (1980). Schemata: the building blocks of cognition. In R. J. Spiro, B. C. Bruce, & W. F. Brewer (Eds.), *Theoretical issues in reading comprehension. Perspectives from cognitive psychology, linguistics, artificial intelligence, and education*. Hillsdale, NJ: Erlbaum Associates.

Salomon, G. (1990). Cognitive effects with and of computer technology. *Communication Research, 17*(1), 26–44.

Salomon, G., Globerson, T., & Guterman, E. (1989). The computer as a zone of proximal development: internalizing reading-related metacognitions from a reading partner. *Journal of Educational Psychology, 81*, 620–627.

Salomon, G., Perkins, D. N., & Globerson, T. (1991). Partners in cognition: extending human intelligence with intelligent technologies. *Educational Researcher, 20*(3), 2–9.

Voss, J. F. (1988). On the solving of ill-structured problems. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The nature of expertise* (pp. 261–286). Hillsdale, NJ: Erlbaum Associates.

Voss, J. F., Greene, T. R., Post, T. A., & Penner, B. C. (1983). Problem-solving skill in the social sciences. In G. H. Bower (Ed.). *The psychology of learning and motivation: Advances in research theory* (Vol. 17, pp. 165–213). New York: Academic Press.

Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching, 32*(5), 521–534.

Zhang, J. (1997). The nature of external representations in problem solving. *Cognitive Science, 21*(2), 179–217.