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Abstract

We compared cognitive processing of two complex arithmetic word problems by college students randomly assigned to four different situating tool and social contexts: individualized problem solving with pen and paper; pair problem solving with pen and paper; individualized problem solving on TAPS, a computer-based problem solving tool; and collaborative problem solving on TAPS. Although they solved identical word problems, TAPS users differed from users of conventional tools in that they required relatively more time for problem solving, spent more time in planning activity, and proportionately less time reading. With respect to the influences of social (versus individual) problem solving, collaboration also produced significantly more planning behavior, such that the combined use of TAPS and collaboration produced a marked increase in planning. Also, significantly more behavior associated with metacognitive monitoring occurred in the protocols for pairs. There was no evidence that use of the TAPS tool changed the social nature of the collaboration. However, a qualitative analysis yielded interesting information regarding negotiation processes underlying pair problem solving. For example, we saw specifically some reasons why untrained pair problem solving does not proceed naturally and smoothly. Results are interpreted in terms of situated cognition theory, although symbolic processing theories also can explain much of the data.

Is Problem Solving Situated?

Numerous theorists (e.g. Vygotsky , 1978; Lave and Wenger, 1991; Newman, Griffin, & Cole, 1989) have suggested that thinking is both physically and socially situated, meaning that problem tasks are formed and changed by the tools and social settings that situate the problem. We hypothesized that the "same" problem-solving task would be altered by different thinking tools and social structures in the sense that the different situating conditions would influence cognitive processing in predictable ways. We compared cognitive processing of two complex arithmetic word problems by college students who were randomly assigned to four different situating tool and social contexts: individualized problem solving with pen and paper; pair problem solving with pen and paper; individualized problem solving on TAPS, a computer-based problem solving tool; and collaborative problem solving on the TAPS system. Our study has relevance for educational practice because it examines typical cognitive processing as might occur in typical educational settings. Both individual and collaborative work with word problems is common in K-12 and adult education classes concerned with developing problem-solving ability. Also, TAPS is implemented in adult educational centers and resembles other reflection-type computer tools that have been developed in recent years for problem solving instruction (e.g., Collins & Brown, 1988; Lajoie & Derry, 1993).

Background: Description of TAPS System

TAPS is a computer-based instructional tool designed to help students develop metacognitive skills and awareness, where *metacognition* refers to one's knowledge of the thinking process itself and how to control it. Examples of metacognitive processes targeted by TAPS include strategic planning and comprehension monitoring. Metacognitive instructional goals are justified by analyses of typical problem-solving difficulties (e.g., Derry, 1989; Schoenfeld, 1987), which have shown that many adult problem-solving errors are due to metacognitive failure rather than, or sometimes in addition to, lack of mathematics concepts.

An example screen display from TAPS is shown as Figure 1. In designing TAPS, we embraced Vygotsky's (1978, trans) notion of cognitive tools --objects provided by the learning environment that permit students to incorporate new auxiliary methods or symbols, which otherwise would be unavailable, into their problem-solving activity. The major cognitive tool provided by TAPS is a graphics interface that facilitates construction of problem trees, network structures showing interrelationships among all relevant sets in a problem situation, specifying the subgoal structure of the problem, and illustrating a solution path. By labeling the tree, students also make explicit their *semantic* understanding of concepts and relationships that underlie their choice of arithmetic operations. Such trees provide graphic reifications of abstract structures that otherwise would be implied, making them public and available for discussion, manipulation, and comparison. Theoretically, this type of environment should encourage and afford reflection and metacognitive awareness (e.g., Reusser, 1993; Collins & Brown, 1988), producing positive immediate and residual effects on problem solving.

Method and Data Source

Volunteer subjects, who identified themselves as weak in mathematics, were solicited from a large undergraduate educational psychology course and received course credit for

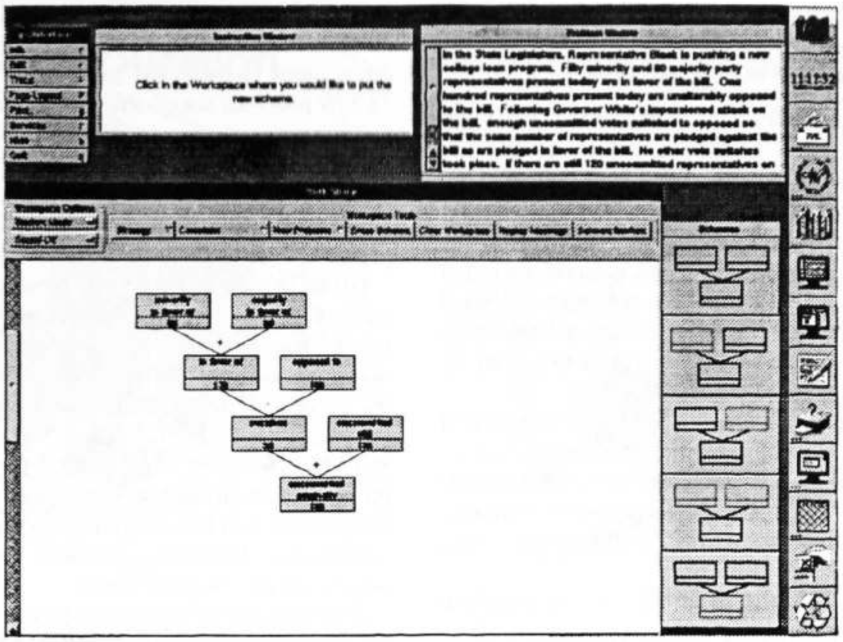

Figure 1: the TAPS screen

participation. Forty-eight students were randomly assigned to one of four treatment conditions. In Treatment 1, sixteen students worked collaboratively in pairs on the TAPS system. Each session consisted of working one training and one practice problem on the system, followed by the "pizza" and the "politics" problems, in counterbalanced order. The politics problem is given as an example:

> *In the State of Forgottonia, Representative Black is pushing a new college loan program. Fifty minority and 80 majority party representatives present today are in favor of the bill. One hundred representatives present today are unalterably opposed to the bill. Following Governor White's impassioned attack on the bill, enough uncommitted votes 'switched' to opposed so that the same number of representatives are pledged against the bill as are pledged in favor of the bill. No other vote switches took place. If there are still 120 uncommitted representatives on this bill, how many were uncommitted before Governor White's speech?*

Treatment 2 was like Treatment 1, except that eight students worked their problems on TAPS individually and were instructed to think aloud during problem solving. In Treatment 3, eight student pairs worked collaboratively on identical problems using only standard tools (pen, paper and a calculator). In treatment 4, eight students worked independently using standard tools while thinking out loud.

Sessions were videotaped, resulting in eight tapes for each condition. To minimize effects of unfamiliarity with TAPS, as well as to achieve a manageable data-analysis task, only the second experimental problem from each protocol was used. Analyses thus combine data from two word problems, balanced across cells, which was supported by analyses that failed to differentiate between the problems.

Effects of Social Condition and Tool Use on Metacognition and Interaction

Since TAPS was designed to promote both metacognition and more productive and reflective collaborative problem solving, we hypothesized (1) that the four different situating conditions represented in this study would significantly alter metacognitive processing; and (2) that the TAPS tool itself would significantly alter the social interaction of pair problem solving. To permit testing of these hypotheses, we devised coding schemes for observing and quantifying behaviors associated with various types of metacognitive processing and social cognition. This coding system (See Table 1) evolved through reflective discussions of videotapes and study of the literature that has employed verbal protocol research to study metacognition and social interaction in problem solving (e.g., Schoenfeld, 1987; Clements & Nastasi, 1988; Arzt & Armour-Thomas, 1992). Its reliability, as measured by percentage agreement between independent raters, exceeded .90.

Metacognitive Coding Analysis

The first analysis focused on metacognition. Each fifteen-second interval for each protocol was coded for evidence of the metacognitive processes described in the first half of Table 1. Multiple codes occasionally occurred within single intervals, which was permitted. For example, both reading and comprehension monitoring sometimes occur within the same interval. The four situating conditions were then compared on the basis of total time spent by students in

Table 1: Outline of Major Categories of Coding Schemes

I. Metacognitive Behaviors

READING: A fifteen-second interval was coded "R" if any reading behavior occurred during that interval. Reading is defined as attention paid to the actual words of the problem. The subcategories were: reading, rereading, underlining, focusing, note taking, and inferencing.

PLANNING: This code was used if the interval included decision-making about what to do. The subcodes included range (distant or immediate), direction (forward or backward), goal (directed or undirected), and what (operation, goal, or strategy).

MONITORING: An interval was coded as monitoring if it included thinking about thinking. When monitoring was of the interface use instead of the word problem, the interface code was recorded as well. The sub-categories included: error checking; comprehension monitoring; and questioning/clarifying.

INTERFACE: Any attention paid directly to the interface was coded.

CARRYING OUT: This code was reserved for calculating and other overt activity associated with solving the problem, often in the absence of noticeable metacognition.

II. Social Behaviors

OBTAINING INFORMATION/HELP FROM OTHER. Subcategories included: Asking; Attending to; Clarifying other's meaning; Using other's idea; Consensus testing. (Table continues)

GIVING INFORMATION/ASSISTANCE: Subcategories included: Answering question; Correcting; Contributing opinion or idea; Suggesting action or interpretation; Justifying action or interpretation; Giving affective support; Agreeing.

DISPLAYING NONSOCIAL BEHAVIOR: Subcategories included: Being negative toward task; Criticizing partner; Isolating; Bossing; Not attending.

EPISODES: These were coded series of interactions overlaying other codes noted above. Subcategories included: Conflict/argument; Conflict resolution; Negotiation; Leadership; Domination.

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problem-solving activity and also on the basis of what types of metacognitive activity were observed (expressed as percentage of time spent in categories of Table 1). Results are depicted in Figure 2a-f.

Statistical tests for main effects (pen/paper versus TAPS and pairs versus individuals) for the categories of reading, planning, monitoring, and carrying out a solution were computed using adjusted Mann-Whitney U tests, a procedure suitable for small samples that does not require homogeneity of variance. As indicated by Figure 2a, students working with the TAPS tool spent nearly four times longer working on their experimental problem compared to subjects in the non-TAPS conditions, a clearly significant difference. It was possible to adjust these means by removing time spent attending to the computer interface, on the assumption that additional time added by the interface is possibly irrelevant since it likely would be reduced with more practice. This adjustment is reflected in Figure 2c, where bars labeled "TAPs problem time" show time spent in problem-solving activity with interface time removed, and can be compared to "TAPS total time," which includes time spent attending to interface. In both analyses, the time difference was marked: TAPS users required much more time to solve their problems.

Given this difference, it is natural to ask whether TAPS subjects performed noticeably better or worse than subjects using pen, paper, and calculator. The probability of obtaining a correct solution was .50 (4 out of 8 protocols) for Pen/Paper-Individual, .50 (4 out of 8 protocols) for Pen/Paper-Pair, .875 (7 out of 8 protocols) for TAPS-Pair, and .750 (6 out of 8 protocols) for the TAPS -Individual group. This difference is not statistically reliable, as our sample size was too small to detect a treatment effect of this magnitude. However, that both TAPS groups excelled is suggestive of a positive trend.

Several a priori hypotheses were advanced with respect to the metacognitive categories of planning and monitoring. It was expected that both working in pairs and TAPS use would increase planning. Employing adjusted Mann-Whitney U-tests we determined that pairs carried out significantly more planning activity than did individuals ($z=2.47$, $p<.05$), and TAPS subjects conducted significantly more planning than did subjects using pen and paper ($z=1.97$, $p<.05$). The test for the interaction was not statistically significant ($z = -0.544$); however, the additive effect of TAPS and pair collaboration was to strongly increase planning behavior, as indicated in Fig. 2b.

In addition, it was expected that pairs would display relatively more monitoring behavior than individuals as a natural consequence of mutual engagement in problem solving. It was also anticipated that TAPS would increase this monitoring behavior, which would result from making abstract aspects of problem solutions more concrete and visible, thus prompting more discussion and questioning. As shown in Figure 2d, pairs carried out significantly more monitoring than did individuals ($z = 4.35$, $p< .05$), but the difference between TAPS and non-TAPS subjects was not statistically reliable ($z = 0.31$).

Tests for the reading and carrying-out phases also were conducted, revealing one statistically significant main effect: Those using TAPS spent only 30.34% of their problem-solving time reading, whereas subjects using standard tools spent nearly 70% of their problem time in activity that could be characterized as reading (see Fig. 2e).

Social Coding Analysis.

The purpose of this analysis was to compare and describe the social interactions that occurred during pair problem solving both with and without TAPS. Each 15-second interval in pair protocols only was coded using the social interaction coding scheme outlined at the bottom of Table 1. Again, multiple coding of intervals was permitted. For example, within the same interval, both helping behavior and negative attitudes might be observed. The TAPS and non-TAPS pairs were then compared for each major category

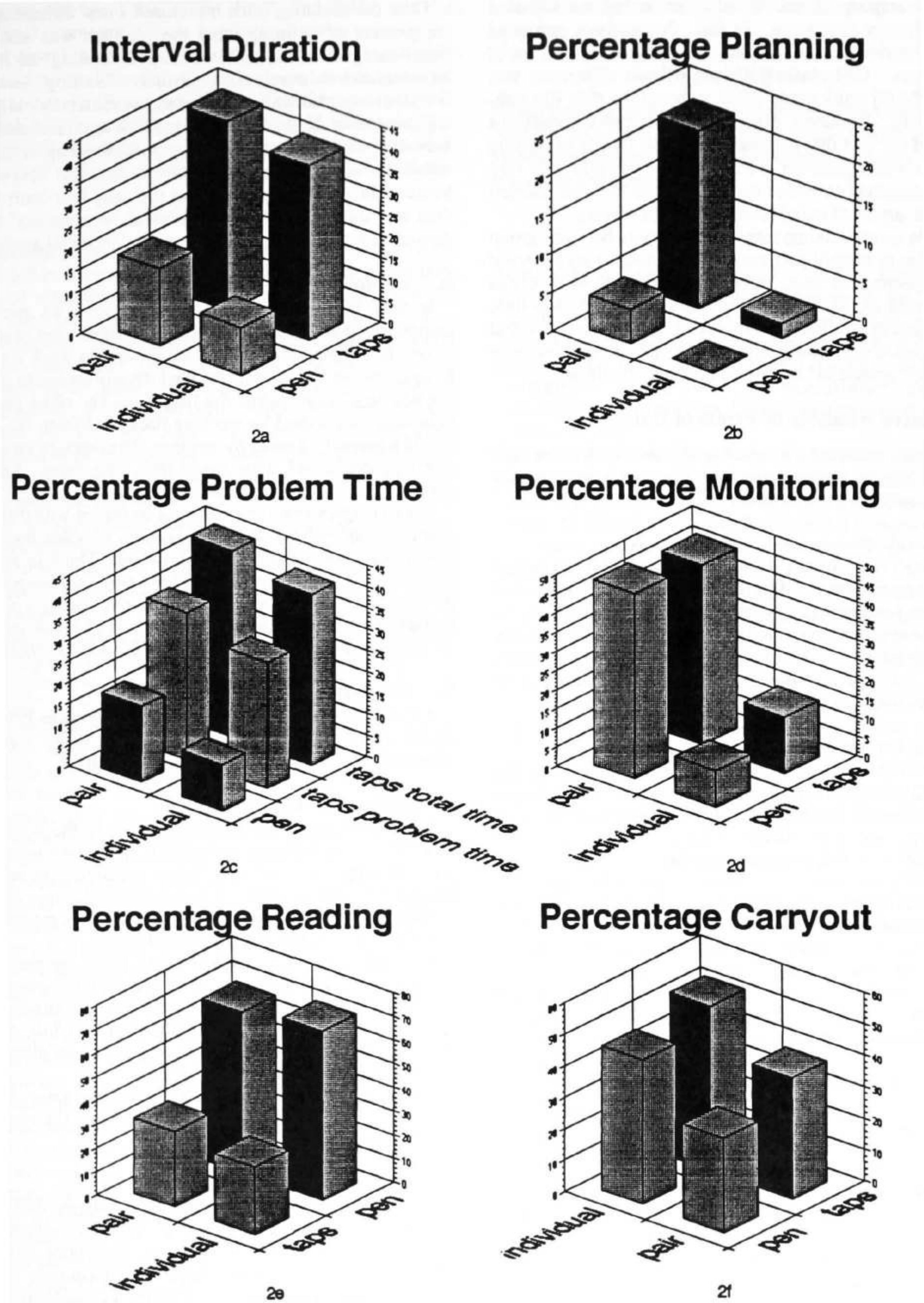

Figure 2a-2f: Treatment duration (expressed as total number of coding intervals) and mean percentages of those intervals associated with types of cognitive activity: four treatment groups compared.

and sub-category of social behavior, using the adjusted Mann-Whitney procedure. In sum, this analysis produced only weak evidence that tool use changed the nature of social interactions. One statistically significant difference was found: TAPS pairs made more suggestions than did non-TAPS pairs. However, given the number of comparisons made and the fact that no other test in the family of helping behaviors was significant, we concluded there was only very modest statistical evidence that differential tool use affected the social aspect of collaborative problem solving.

Perhaps more striking were some obvious between-group similarities in overall patterns of social interaction observed from inspecting the data. In both conditions, more time was spent giving as opposed to receiving help. There was little argumentative conflict or domination, although a great deal of negotiation occurred in both conditions. Also, there were almost no "nonsocial" behaviors in either condition.

Qualitative Analysis of Protocol Data

We also conducted a detailed qualitative analysis of each protocol. Space prohibits sharing of protocols, so summary findings only are given below.

1. Social Dominance.

Although our initial coding of protocols did not reveal much extreme social dominance, a socially subtle but definitive intellectual leadership by one partner over the other was observed in virtually every protocol. Occasionally this leadership role would be swapped during problem solving, but one member of the team could always be defined as leading the process of meaning construction.

2. The Importance of Insight

The problem solving in our samples exhibited a decided Gestalt-like quality in that it proceeded largely by data-driven search followed by insight. Pairs proceeded by reading, reflecting, and sometimes floundering until an "Aha experience" occurred, often quite suddenly.

Efficient pairs behaved as follows: After a short period of thoughtful reading and reflecting, a single insight that is key to the solution is experienced by one partner, who is able to quickly bring the other partner to understanding of the insight. They solve the problem with little monitoring or checking. Inefficient but successful pairs also relied heavily on data-driven search and insight. However, inefficient pairs often experienced a number of piecemeal insights rather than one key organizing framework. Sometimes an insight can be incorrect; or it may a relevant one but not the full "key" to the solution. Weaker pairs had difficulty evaluating their insights and some quickly abandoned good insights without exploring their implications.

3. Peer Tutoring and Explaining

Whenever one person experienced what they perceived to be an important insight into the problem, they inevitably attempted to share it with the partner. This was always the point where some degree of coaching or peer tutoring occurred, as the person with understanding tried to coax the partner to see and accept it.

Thus, collaborating often introduced a new dimension into the process of defining what the problem was about: a significant part of the problem became "selling" an idea to an uncertain or questioning partner. "Selling" involved insistent explaining and was sometimes slightly argumentative. If the other partner failed to understand, or if they were working on a competing understanding, resistance would be expressed as doubtful questioning. However, because this "selling" process was typically less confrontive than was arguing, it was often coded as "negotiating" rather than as "conflict" in our initial quantitative social analysis.

4. Competing Understandings

It was very common for two solvers to promote competing understandings and/or approaches. For example, in one protocol, a partner was attempting to work forward from givens and repeatedly scrolled the workspace to permit the adding of steps below the first one. The other partner, believing they would be working backward from the goal, would repeatedly counter by scrolling the computer screen so that they could add steps above their first entry. Neither partner understood what the other was thinking.

Since complex word problems can be solved with different strategies and solution paths, it is quite possible that both competing understandings may be valid. Thus, in several protocols, the dominant partner was selling a viewpoint at the expense of another also valid viewpoint held by a weaker partner. The solution in such protocols is as much socially as "cognitively" negotiated (Clements & Nastasi, 1992).

5. Computer Difficulties

A factor accounting for some speed differences between TAPS and non-TAPS conditions was that a few students were slow and awkward with a computer mouse.

6. TAPS and Representation

TAPS can complicate problem solving in the following way: For some subjects using the system there were two separate stages to problem solving: obtaining an answer followed by the problem of representing the tree on the system. Sometimes the representation stage was regarded as a check on an original solution hypothesis.

By contrast, for some subjects using TAPS the processes of representation and solution finding were fully integrated. That is, some subjects employed the TAPS tools to help them understand and solve simultaneously while others employed TAPS to help them make visible an otherwise hidden, mental problem solving process.

This added complication affects social interaction to the extent that it makes the problem, and hence the required communication, more complex.

7. Heuristics and Strategy

The most common problem solving strategy was data-driven search for insight. For better problem solvers, this strategy was efficient and effective. For poor problem solvers, this strategy had a different appearance. Less effective problem solvers sometimes consciously used heuristics to help them search the problem space. For example, one inefficient pair tried several heuristics, such as "examine the goal statement first" and "pull out the numbers." Sometimes these heuristic activities successfully led to insights and sometimes they did not. In some protocols, several heuristic strategies were tried and these all led to some significant insight, but these insights were not pursued deeply and long enough to lead to understanding. Such problem solvers appeared to jump from idea to idea, abandoning each before important relationships were found.

Discussion

Although they solved identical word problems, TAPS users differed from users of conventional tools in that they required relatively more time for problem solving, spent more time in planning activity, and proportionately less time reading. With respect to the influences of social (versus individual) problem solving, collaboration also produced significantly more planning behavior, such that the combined use of TAPS and collaboration produced a marked increase in planning. Also, significantly more behavior associated with metacognitive monitoring occurred in the protocols for pairs. Our quantitative analysis produced no strong evidence that use of the TAPS tool changed the social nature of the collaboration. However, the qualitative analysis indicated that for some (though not all) subjects the TAPS tool tended to "split apart" problem solving into separate representational and problem solving issues, which complicates the social problem solving process. Also, the qualitative analysis demonstrated that problem solving in pairs involves a particular combination of cognitive negotiation and social dominance that we referred to as "selling." Finally, while there was no evidence that collaboration improved problem solving efficiency or outcome, there was some suggestive evidence that TAPS use might increase accuracy.

Our findings add validity to the situated cognition viewpoint, that the same problem-solving task under different social organization and tool conditions is not the same task at all. Nevertheless, most processing differences among treatment conditions can be easily explained by more traditional symbolic processing theory. For example, observed increases in planning behavior can be explained by reference to the ideas that introduction of unfamiliar tools or social conditions promotes a novice style of problem solving, widely believed to be heuristically guided. Also, the "pulling apart" (e.g., Newman et al., 1989) of the TAPS problem solving task into conscious representational and problem solving issues also can be explained in terms of the information processing idea that students have not yet automated their use of TAPS interface tools. However, the situated viewpoint does direct attention to influences of the social context on processing. Our qualitative analysis in particular yielded interesting and important information regarding the cognitive processes of social problem solving. Similar to what Teasley (1992) observed with children, we see reasons why untrained pair problem solving does not proceed naturally and smoothly for adults.

It is clear that distinctive processing changes do occur when new tools and social conditions are introduced as alterations in standard problem solving procedures. As such introductions take place routinely in classroom and other real-world environments, further research on their impacts is necessary and useful.

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