The Emergence of Abstract Representations in Dyad Problem Solving

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ABSTRACT

Three experiments examined whether group cognitions generate a product that is not easily ascribed to the cognitions that similar individuals have working alone. In each study, secondary school students solved novel problems either working as individuals or in two person groups called dyads. An examination of their problem-solving representations demonstrated that the dyads constructed abstractions well above the rate one would expect given a “most competent member” model of group performance applied to the empirical rate of individual abstractions. In the first experiment dyads induced a numerical parity rule for determining the motions of linked gears four times more often than individuals, who instead tended to rely exclusively on modeling the gears’ physical behaviors. In a second experiment requiring the construction of visualizations on the topic of biological transmissions, dyads made abstract visualizations (e.g., directed graphs) significantly more often than individuals. In a third experiment requiring a visualization of organisms and their habitat requirements, dyads made abstract visualizations (e.g., matrices) five times more often than individuals, who instead tended to draw pictures. These results are striking because a long history of experimentation has found little evidence that group performances can match the performances of the most competent individuals, let alone exceed them. The extremely high frequency of abstract representations among dyads suggests that the abstract representations emerged from collaborative cognitions not normally available to isolated individuals. The results are interpreted to be a natural result of the collaborative task demand of creating a common ground. To facilitate discourse dyads negotiated a common representation that could serve as a touchstone for coordinating the members’ different perspectives on the problem. Because the representation bridged multiple perspectives of the problem structure, it tended to be an abstraction.

Despite the common sense that working in small groups can produce distinct cognitive products compared to working alone (e.g., Schoenfeld, 1989), a substantial body of experimental research directly contrasting groups and individuals has failed to demonstrate unique outcomes attributable to group work (for reviews see Hastie, 1983; Hill, 1982). In these studies, groups often outperform the average individual, but do not perform to the level of the pooled results of equivalent individuals working alone. This has been true for a broad range of tasks including induction (Laughlin & Futoran, 1985), problem solving (Kelly & Thibaut, 1969; Marquart, 1955), brainstorming (Dunnette, Campbell & Jaastad, 1963), puzzle solving (Thorndike, 1938), and writing (Fox & Lorge, 1962). For example, subjects in a study by Laughlin and Shippy (1983) cycled between individual and group modes of production until they generated and agreed upon the pattern generating a sequence of playing cards (e.g., alternating spades and hearts). Laughlin's summary of his findings, although based on a unique experimental design, may be generalized to many experimental results thus far, "Collective induction in the strong sense of a correct group hypothesis that none of the group members had [previously] proposed as an individual was extremely rare" (Laughlin & Shippy, 1983, p. 97). Overall, this body of experimental data suggests that joining individuals into a group precipitates few cognitive products, other than critique, that are uniquely attributable to the condition of working in a group (Johnson & Torvicia, 1967; Laughlin & Futoran, 1985; Shaw, 1932).

Against the backdrop of the numerous failures to demonstrate strong performance differences between groups and individuals, the purpose of the current paper is to describe three experiments that used a fresh source of evidence to compare the results of group and individual problem solving. A feature of many previous studies is that the comparisons of groups and individuals were made in terms of efficiency measures such as time to completion or percent correct. Efficiency measures are important, but they may not be the most likely place to find a cognitive product attributable to group work, particularly in short duration studies. For example, process losses associated with coming to an initial understanding of one's partner may undermine the advantages of having the resources of multiple people. Instead of looking for efficiency effects, I began the search for the effects of group cognition by considering the potential outcomes of collaborative task demands, such as coming to a mutual understanding of problem materials. The results show that if one compares the types of representations that groups and individuals construct to solve problems, rather than the final problem-solving performances themselves, group cognitions sometimes yield a product that is not easily ascribed to the cognitions that similar individuals had working alone. In particular, groups have a tendency to construct representations that are more abstract than individuals' representations.

The possibility that collaborative problem-solving generates abstract representations may have implications for the design of instruction and workplace practices. Abstract representations play a central role in many aspects of learning, problem-solving, and understanding. For example, they provide a way to illuminate structure across multiple contexts, as in the case of noting a linear trend in disparate situations. Abstractions also provide a bridge between perceptual experience and theoretical understanding, as in the case of constructing a standarized unit of measurement. If groups naturally construct abstractions, then one can begin to think of situations in which it would be particularly advantageous to use groups. However, it is first necessary to consider the conditions under which a group might be expected to generate an abstract representation.

The following paragraphs describe the rational analysis that led to the designation of three task demands that, if met, might lead to collaborative representations that are more abstract than individual representations. The intent of the analysis is to describe situations that would support abstraction rather than to describe the process of abstraction itself. For example, the situational description includes process elements such as discourse. But this description of process is not intended to be a "process account" in the sense of specifying a series of necessary or sufficient psychological steps for yielding abstraction. Instead, it is meant as a description of a dynamic situation that helps set the stage for abstraction, however abstraction ultimately occurs. Detailed process accounts are important, but in the case of abstraction, they are fraught with theoretical complexities that can detract from the basic comparison of group and individual production. For example, the question of how abstraction could possibly occur overlaps with fundamental issues that separate realist and idealist perspectives on cognition. From the realist perspective, abstraction should be described as a process of uncovering or discriminating the objective structure of the world. From the idealist perspective, abstraction should be described as a process of constructing or imposing a structure on the world. To navigate these and other fundamental divisions, and to stay within the scope of the group and individual comparison, the simpler approach taken here is to consider natural situational supports for group abstraction. Furthermore, rather than developing a potentially contentious definition of abstraction, I have operationalized abstraction for each experimental task such that it captures distinct qualitative differences in subjects' representations as found from pilot studies. Hopefully, these operationalizations approximate the reader's sense of abstraction.

The first of the three task demands that may support abstraction reflects a salient characteristic of group work; individual members often have different perspectives on a problem. For example, the same word or project description can mean different things to different group members. These different perspectives create communicative challenges. If not resolved, they present opportunities for miscommunication. By the same token, multiple perspectives present opportunities for successfully building on the ideas of several people. The possibility proposed here is that the multiple viewpoints contained in small groups can sometimes serve the same role that multiple examples serve in supporting the induction of abstractions (Gick & Holyoak, 1983). Their diversity affords an induction of a structure that spans superficial differences. For example, if group members successfully negotiate the similarities between their idiosyncratic representations of a problem, one might expect the resulting group representation to be more abstract and general than any of the individual representations. It might capture consistencies between individual representations and lose idiosyncratic surface features. Moreover, groups, like individuals, may need to introduce additional structure to accommodate non-intersecting perspectives, ideas, or examples into a single representation.

A second task demand that may facilitate abstraction occurs when group members need to integrate their perspectives. One can imagine several situations in which groups do not need to integrate perspectives. For example, a group may simply adopt the perspective of one individual within the group. Prior research in psycholinguistics and social psychology has demonstrated that one situation in which group members do frequently negotiate a collaborative representation is when explicit task demands require the resolution of mutual knowledge problems. Mutual knowledge refers to conversants' knowledge that their references have the same meaning for other participants in a conversation (Clark & Marshall, 1981; Thibaut, Strickland, Mundy & Groding, 1960). Typically, the guarantee of mutual knowledge comes either from the common ground of shared cultural convention or from external references whereby an individual can point to what he or she means (Krauss & Fussell, 1990). Krauss and Weinheimer (1966) showed that by denying partners the assumption of conventional naming and access to shared external reference, they will negotiate a common representation that consolidates their respective representations. In these studies two individuals on either side of an opaque screen had to array their identical sets of novel tanagram figures into identical sequences. To accomplish this task, they had to develop a way to refer to each figure. For example, one individual might call a shape (e.g., a square with triangles on the upper corners), "The dog with floppy ears," while the other calls it, "The open carton." Subsequently, there is a give and take as partners attempt to ensure they are talking about the same tanagram. As a result of this negotiation, the individuals usually settle on a single referring expression such as, "The box and ears." Although one would be hard pressed to argue that this final expression is more abstract or qualitatively different than the individuals' initial expressions, the example demonstrates how explicit problems of mutual knowledge lead to the construction of a collaborative representation that can ensure shared meaning (Garrod & Anderson, 1987; Schrober & Clark, 1989). It seems reasonable that similar effects could develop in more natural and less explicit situations of limited mutual knowledge. For example, learning in school often involves problems of mutual knowledge. Ideas are new, and therefore students do not have access to their conventional meanings. Moreover, the referents of ideas are often unavailable or relational, thereby preventing the use of pointing to disambiguate reference. If given the opportunity, students might recognize and attempt to resolve mutual knowledge problems at school. If true, this presents an interesting alternative to didactic instruction for developing shared meaning within the classroom.

A third task demand that should be supportive of abstraction occurs when structured relations are important to problem solving. In the previous example of the screened reference study, the structure of each tanagram figure played an incidental role to the overall seriation task. As a result, subjects could simply develop a mutual label for each figure rather than develop a mutual representation of the structure of each figure. Labeling activity does not provide a strong basis for the creation of abstractions. In particular, the label in this case is mapped onto a single instance and is not developed to map onto multiple instances or the relations that bind instances. In contrast, in those cases where the potential structure of a situation plays an important role in problem solving, there should be more activity dedicated towards achieving a common grounding in the structure. This presents a better opportunity for groups to develop a representation that captures an abstract relational structure.

To investigate the possibility that the three conditions -- multiple perspectives, mutual knowledge problems, and task relevant information structures -- would support abstraction in groups, the following experiments examined the representations that adolescents, paired into dyads or working individually, constructed in two problem domains. One task was to determine the rotary motions of imaginary gears. A second task was to draw inferences from texts that described complex relations within various domains of biology. Each task included several features that differentiated them from prior studies comparing groups and individuals.

One feature was an implicit task demand to build mutual knowledge; the referents of the problems were novel or described in novel configurations, and they were not observable by members of a dyad. The assumption was that this would initiate the process of constructing a common ground to resolve different perspectives on the novel tasks. A second feature of the tasks was an amenability to external representation. Among the possible tasks that include problems of mutual knowledge, the two used in these studies were chosen because subjects could construct external representations to help achieve a common ground. For example, in the mechanical reasoning task subjects could use their hands to represent the gears, and in the biology tasks subjects were directed to construct visual representations. This may be important for the adolescents in these studies, because without the support of an external touchstone, the demands of constructing a common ground for discussing complex relations may have been inhibitory. A third feature of the two tasks was the multiple relationships between the problem elements (e.g., the causal connections between gears and the interconnections between organisms). These relationships ensured that there was a relevant structure that could emerge in the processes of negotiating a common ground. A fourth feature of the problems was that the subjects' mediating representations were susceptible to reasonable judgments of abstractness. For example, in the case of the gear problems, it was easy to judge whether subjects were gesturally modeling the behaviors of the gears, or whether they were deriving an answer using a more abstract parity rule. The fifth task feature allowed for the possibility of emergent behavior. The dependent measure of primary interest was not problem-solving efficiency as the participants might have believed. The critical measure was whether they constructed mediating representations with abstract qualities. Because the participants were not aware of this experimental interest, it was possible to see if abstractions naturally emerged from collaborative activity.

To judge the extent to which cognitive products emerge from dyad problem solving, there are weak and strong models of between-subjects evidence. In the current case of categorical outcomes, the weak model involves a standard comparison of the rates of abstraction resulting from individual and dyad work. The method is considered weak because it does not demonstrate that a higher rate of dyad abstraction was due to cognitions found more frequently in a dyad setting. For example, dyads could exhibit reliably higher performance on an addition question by simply allowing the most able member of each dyad to do the arithmetic. To control for this possibility, numerous strong models pool individual performances to test whether group performances could be partitioned into individual performances (e.g., Davis & Restle, 1963; Faust, 1959; Lorge & Solomon, 1955; Restle & Davis, 1962; Steiner & Rajaratnam, 1961; Thomas & Fink, 1961). The class of models most appropriate for the current experiments has been called alternatively the best ability model, the most competent member model, the disjunctive model, the rational model, or the truth-wins model. For categorical outcomes, these models (henceforth the truth-wins model) posit that the maximal possible group performance resulting from a discrete combination of individual performances occurs when the most able member in the group (or, the member with the "truth") makes the response. Computationally, the optimum theoretical probability of a dyad reaching a correct answer is found by calculating the probability that any given dyad would include at least one member who could solve the problem in isolation.[1] This theoretical level of performance sets a threshold that, if exceeded, indicates that there is a positive "interaction" among problem solvers that cannot be attributed to the "main effects" of either or both individuals in the dyad.

EXPERIMENT 1

In the first experiment, dyads and individuals heard eight versions of a simple gear problem: *Five meshing gears are arranged in a horizontal line much like a row of quarters on a table. If you turn the gear on the furthest left clockwise, what will the gear on the furthest right do?* Each problem differed only with respect to the number of gears in the total chain. Previous research has shown that individuals and groups can solve these problems with little difficulty (Schwartz & Black, 1994). However, the measure of primary interest in the current case is not whether dyads solve the problem more effectively than individuals, but whether dyads are superior at inducing an abstract parity rule for solving the problems. Among the numerous possible parity rules, one reasonable example is as follows: *If there are an odd number of gears; then the first and last gears will turn the same direction. If there are an even number of gears; then the first and last gears will turn in opposite directions.*

Most people, when initially solving the gear problems, simulate the motion of each gear with their hands. The hand gestures are a particularly salient form of concrete representation in that they stand as external surrogates for actual gears; five gears require five distinct hand gestures. After a number of problems about gear chains, some people induce a parity rule. Subsequently, these people are able to reason over numerical properties rather than gears and motions. It is the ability to reason about the numerical attributes of the problem without modeling the gears themselves that makes the parity rule an abstract representation. The separation of attributes from their referents is a reasonable indicator of abstractness. For example, when one imagines the attribute of height in a non-abstract fashion, there must be a referent with that height. On the other hand, if one uses an abstract measurement like feet and inches, then it is possible to think about the attribute of height (e.g., 5' 6") without having a specific referent in mind.

There are several convergent ways to monitor whether an individual or dyad induces a parity rule (Schwartz & Black, 1994). The simplest is that subjects often spontaneously mention some version of the rule or use the words "odd" or "even" in conjunction with the answer to the problem. For example, "All the odd ones are clockwise," or, "Nine gears is an odd number, so the last gear turns clockwise." A second source of evidence comes from hand gestures. People typically use hand gestures until they induce a parity rule, at which point the hand gestures cease. The third source of evidence comes from response latencies. Modeling numerous gear motions takes more time than simply inferring the parity of the problem. Once people employ a parity rule, problem-solving latencies can be an order of magnitude less than when they modeled the problem. So, for example, if problem-solving latencies drop from 30 seconds to 2 seconds and gesturing ceases, there is reasonable evidence that subjects have induced a parity rule even if they do not explicitly mention it.

Each of the three sources of data -- verbal, gestural, and temporal -- helps indicate whether and when subjects have induced a parity rule. Although the induction of a parity rule is readily apparent to multiple coders, an extra problem was included to indicate rule induction in a fashion less open to interpretation. For the first seven problems, subjects reasoned about chains of three to nine gears. The eighth and final problem used 131 gears. If subjects have not induced a parity rule prior to this problem, latencies should be lengthy as subjects model numerous interacting gears or invent less cumbersome methods for solving the problem. In contrast, if subjects have induced a parity rule, a problem of this magnitude should be solved as quickly as smaller problems, because determining the oddness or evenness of a number does not depend on its magnitude.

Method

Subjects.

Thirty-eight 10th- and 11th-grade boys at a New York City parochial school consented to participate in the experiment. The boys represented a broad spectrum of ethnicity.

Design.

The only design factor was between subjects with boys randomly separated into 14 individuals and 12 dyads. The first seven gear problems were used as stimuli for inducing the parity rule. The eighth problem was used to ensure proper coding as to whether subjects had induced the parity rule. The problems included 3 through 9 gears and 131 gears. Problems were either presented in ascending numerical order, or in the order of 3, 5, 4, 6, 7, 8, 9, and 131. Presentation order was counter-balanced across grouping condition and had no influence.

Procedure.

Each individual or dyad worked in front of a video camera with the experimenter screened from view. Students were told to work on the problems until they were confident enough to place an imagined bet of five dollars on their solution. When an answer was incorrect, students were instructed that they should try again, continuing until a correct answer was reported. Dyads were given the additional instruction that both members had to agree on the answer before reporting. All students solved a filler problem to practice fulfilling the directives (i.e., determining the behavior of a car that steered by the front and rear wheels). The experimenter then told the dyad or individual that all of the problems involved gears much like the two inch spur gear held up by the experimenter. The experimenter also told the students to assume that each gear meshed with its nearest neighbor(s). Students then successively solved eight gear problems. Students were told the number of gears, the clockwise direction of rotation of the gear on the left, and asked to report the direction of rotation of the gear on the right. After completing the problems students were asked if they discovered anything that helped them solve the problems and were told the purpose of the experiment.

Results

Two independent coders, one blind to the experiment's purpose, had 100% agreement on whether a dyad or individual had induced a parity rule prior to the 131 gear problem. Latencies for the 131 gear problem corroborated these codings. Problem-solving times on the 131 gear problem for those who had induced a parity rule (mean = 6.7 secs, SD = 6.8) were well below those who had not (mean = 63.1 secs, SD=56.7). For both the dyads and the individuals who induced a rule, the mode and the mean of induction were during the fourth problem.

Fourteen percent of the individuals and 58% of the dyads induced a parity rule during the seven problems. These rates of induction are significantly different; Z=2.58, n=26, p<.01. This fourfold advantage for the dyads doubles the optimal expectations derived from a truth-wins combination of individual performances (cf. *Model A* of Lorge & Solomon, 1955). This model predicts that the optimal probability of successful group induction should be the probability that any one member or both members of the dyad would have discovered the rule in isolation. Given that 14% of the individuals induced the rule, there is a .265 probability that either or both members of a dyad would induce the parity rule. Following the original Lorge and Solomon (1955) method for estimating significance by this model, there is a low probability that the difference between the expected probability of .265 and the found dyad probability of .58 could be so large by chance; $p<.051$.[2] The Lorge method does not consider the variability in the estimate of the individual probabilities nor the direction of a statistical test designed to judge a group advantage. If .265 is used as a variable estimate of the theoretical dyad performance, the difference from the actual dyad performance is significant in an *a priori* one-tailed test; $Z=1.64$, $n=26$, $p<.05$.

One possible explanation for why dyads more frequently induced a parity rule is that they performed better on the initial problems and that this superior performance created a stronger basis for inducing a rule.[3] This possibility was not empirically supported using two traditional measures of problem-solving performance, speed and accuracy. Subjects who showed superior performance on the early problems did not induce the rule more often than other subjects. Moreover, prior to rule induction, dyads and individuals performed about the same with respect to these two measures of problem-solving performance. Thus, superior problem-solving performance could not have caused dyads to induce rules more frequently.

[Table 1 about here]

Table 1 presents the average within-subject means for correct response time and probability of a correct first answer for the problems that were answered prior to any rule induction. Probabilities of a correct first answer were used because all second try answers were correct. For individuals or dyads that did not induce a parity rule, the means include the first seven problems. For those who did induce a parity rule, the means reflect all problems prior to the problem on which induction occurred. On the problems after inducing a parity rule, latencies were minimal (individuals = 2.7 secs, SD = 2.6; dyads = 4.5 secs, SD = 3.9) and there were no errors. A multivariate analysis crossed dyad/individual by induction/no-induction using subjects' average latencies and proportion of correct first answers (transformed by the arcsine, Kirk, 1982) as dependent measures. Although the small sample sizes and the large variances limited the power of the analysis, there were no significant effects; $F(1,22) < 1.75$ in all tests. The near equivalences of the marginals suggest that a larger sample would not change these null results.

Discussion

The dyads induced an abstract parity rule for solving the gear problems four times more often than the individuals. This rate of induction was roughly two times greater than one would expect if the dyads were operating at the level of their most competent member. Interestingly, if problem-solving speed or accuracy prior to rule induction had been the critical dependent measures, this experiment would not have revealed any differences between dyads and individuals. The favored explanation of these results is that the mutual knowledge demands of communicating about the gear task led to the negotiation of collaborative representations that neither individual would have developed in isolation. In the current experiment, these negotiated representations were not the abstract parity rules themselves. This is because the final step of inducing a parity rule is a singular moment of insight, and one should not expect it to occur simultaneously within both individuals. Instead, as I describe further below, the collaborative representations afforded the inductive insight by producing a shared articulation of the parallel structures, physical and numerical, that are essential to the final abstraction of the parity rule.

Throughout the problem-solving episodes, there were numerous examples of negotiation directed at solving a particular mutual knowledge problem. For example, the dyad members were seated across a low table facing one another, and consequently they often discussed which hand should count as the left or right side of the gear chain. A interesting class of collaborative representations came from tacit, non-verbal negotiation. At first, when modeling the gear problems with their hands, the members of a dyad would have disparate hand motions. For example, a member of one dyad made tiny circular motions with the forefinger while the other member made large turning motions with splayed fingers. By the second or third problem, the hand motions of the dyad members became less distinguishable. In this particular example, each member of the dyad settled on a novel motion that looked as though the hands were holding a virtual gear with the finger tips. This example demonstrates how a collaborative representation can be produced at many levels within group work.

With respect to the abstraction of the parity rule, an important step in the movement towards an abstraction is the casting of numerical properties onto the gestural models. Prior research has shown that individuals who enumerate each gear while they model its rotary motion are more likely to induce a parity rule than individuals who do not explicitly count out each gear (Schwartz & Black, 1994). This makes sense in that the discovery of a parity relationship among gears depends on a simultaneous consideration of physical behaviors and numerical properties. Among the dyads who induced the parity rule there was a common mutual knowledge problem that led to the simultaneous consideration of physical and numerical properties. Typically, one member of a dyad modeled the behaviors of the gears. The second member often watched but could not follow which hand gesture stood for which gear. Subsequently, there was discussion about which gear was currently depicted. For example, one dyad member asked, “Is that the third or fourth gear?” while pointing at the other member’s hands. To resolve this ambiguity, the dyads coordinated their behaviors; one member would model a gear and the other would state its position in the chain. This collaborative and jointly articulated representation contained the necessary coordination of numerical and physical structures to support the insight that all odd-numbered gears turned clockwise.

One alternative to the current interpretation of the results is that the experimental procedures inhibited individual production more than dyad production. For example, the individuals, in the company of an unknown adult and facing a video camera, may have been distracted from the task at hand or may have suppressed tentative parity rules in shyness. Dyad members, on the other hand, because they had the company of a fellow student may have felt less nervous and more inclined to articulate and test their tentative rules. In the following experiments, individuals and dyads worked in the familiar environment of a regular classroom setting. Moreover, they were explicitly required to produce their representations. This should remove production suppression as a potential account of dyad and individual differences in the production of abstract representations.

EXPERIMENT 2

In this experiment, the question was whether middle school and high school dyads would construct abstract visualizations more frequently than individuals. Students received a set of complex sentences from one of eight domains in biology ranging from food webs to DNA tracing. For example, one work sheet briefly described epidemiology and then provided a set of relations. The following example shows four of the eight relational sentences used in the epidemiology problem:

Group Z can pass the disease to group Y and X.
Groups V and U can get the disease from group X.
Group Y can infect group V and group V can infect S.
Group T can pick up the disease from S, W and Y.

The students' task was to generate a non-sentential representation of the sentences such that it could aid in answering two questions. These questions were chosen from a pilot study to include one easy and one difficult question. A moderately difficult question might read:

> Recently a number of people in group Y caught the disease when travelling to a foreign country. Up until now, nobody has had the disease this year. However, you know that group Y will spread the disease to other groups. What group or groups of people do not need to worry about catching the disease that Y now has?

One reason for employing a visualization task to generalize the results of the gear study involved the importance of learning to represent the world in abstract visual ways. Unlike a picture or schematic drawing, a scientific visualization frequently does not resemble its referent. For example, a Cartesian graph of the Gross National Product does not look like the GNP. Instead, it covaries with the GNP -- as the GNP increases the plot climbs the page. Among their many strengths, covariant representations are a powerful way to represent relationships distributed across space and time. Nonetheless, representing referents in abstract visual ways may not be a spontaneous mode of representation for individuals (Novick, 1990; Schwartz, 1993). If the interchanges within student dyads naturally lead to the construction of abstract representations, then situations in which it would be particularly advantageous to use collaborative work could be delineated.

The conjunction of three properties were necessary for a visualization to be considered abstract. 1) *No Transcription*: The visualization could not reflect the surface features of the text presentation such that it was possible to recover the original sentences. For example, if one created a list-like visualization in which each line of the visualization represented one sentence, then one would not have abstracted away from the surface form of the original sentences. 2) *Unified Links*: The representation had to distill the different predicates from the sentences into one or two predicates or connectors. For example, one set of sentences used the verbs, "gives," "sends," "gets," and "receives." If students included four types of relations reflecting the four verbs, then they had not abstracted the single type of connection underlying the relations between the letters in the sentences. On the other hand, if students used arrows to connect letters, this was an abstraction that distilled the fundamental "transmission" relationship into a single convention. 3) *No Semantics*: The students could not ascribe specific referents to the letters used in the relational sentences. For example, one sentence stated, "Organism A supplies energy for organism B and organism C." If students portrayed the A as an apple, they took a given abstraction and made a specific concrete interpretation.

Method

Subjects.

Ninety-one students from two suburban New York public schools consented to participate in the experiment as part of their regular class period. Fifty-two of the students were in 7th-grade Life Science at a middle school. Thirty-nine of the students were in 9/10th-grade Biology at a high school.

Materials.

Separate packets covered eight topics involving the transmission of effects: food chains, water cycles, demographics, pollination, epidemiology, DNA tracing, causality, and cell organelles. On the first page of each packet was a description and an example of the basic concept, along with a discussion of why it was important to biologists and society at large. Below this description there were eight sentences that described the relations between unspecified entities represented by letters (see epidemiology example above). These sentences changed between passive and active voices, used multiple verbs to describe the relationship between entities (e.g., sends and passes), included compound sentences, and distributed the same letters over several sentences. This style of information presentation is similar to that used in the Analytic section of the Graduate Record Exam. The second page of the packet provided space for the visualization. The third page had three problems: one filler question on the background text and two on the information provided in the sentences. Students were allowed to separate the pages.

Design.

The primary contrast was between dyad and individual visualizations. A secondary factor was the grade level of the students. The 7th-grade classes were randomly separated into 20 individuals and 16 dyads. The 9/10th-grade classes were randomly separated into 19 individuals and 10 dyads. A larger sample for the individuals was chosen because their performances served as a baseline for calculating the expected dyad probabilities. Each individual and dyad received a single packet representing one biology topic. Material distribution counter-balanced the eight packet versions by grade and grouping condition. Because of the sample size, some packets were randomly distributed to those remaining students that could not be counter-balanced.

Procedure.

Prior to working on the visualization tasks, all students spent one class period playing prisoner's dilemma (Rapoport & Chammah, 1965) in teams to encourage collaboration in the dyad condition. During the next day's class session, students were directed to work alone or with their randomly assigned partner from the previous day. Individuals and dyads each received a single packet. The students were told that they should read the first page and that they must try to lay out or visualize the sentences from the bottom of the first page on the second page. They were told that a good representation should help them answer the last two questions on the third page but that there was not a right or wrong way to do this. It was pointed out that just copying the sentences would not help very much. Students had 20 minutes to complete the task.

[FIGURE 1 - About here]

Results

Individuals and dyads finished the task within the 20 minute allotment and exhibited no time differences. Using the conjunction of all three indicators of abstraction as the criterion of overall abstractness (i.e., unified links, no transcription and no semantics), the dyads made proportionally more abstract visualizations than individuals; 85% vs. 59% respectively, $\underline{Z}=2.22$, $n=65$ $\underline{p}<.05$. As reflected in Figure 1, the dyad advantage approximated the theoretical expectation derived from the truth-wins model. The grade level by grouping interaction was not significant; $\chi^2(1) = 2.7$, $\underline{p}>.1$, although the right-hand side of Figure 1 indicates a descriptive difference between the grade levels -- the 9/10th-grade dyads constructed relatively more abstract visualizations. It should be noted that every 9/10th-grade dyad made an abstract visualization. This may indicate a truncation of an advantage that the older dyads might have exhibited on a different task.

[TABLE 2 -- about here]

[FIGURE 2 - about here]

Two independent coders, blind to the source of each visualization, had 97% agreement on the three categories of abstraction. Disagreements were resolved by coding conservatively with respect to the hypothesis of a group abstraction advantage. Table 2 provides a breakdown of the empirical and derived probabilities for the three indicators of an abstract representation used in this experiment. Figure 2 provides a representative sample of the visualizations and their codings.

Figures 2a through 2d were coded abstract in all three categories. Each of these visualizations also provides a reasonable organizational structure for the information (Schwartz, 1993). Figure 2e is not abstract in that it does not abstract the basic connective relationship from the different words used to indicate transmission. In Figure 2f, each equation represents a single sentence. As such, it does not abstract away from the sentential surface of the provided information. Figure 2g conveys specific interpretations of the letters. For example, a D did not refer to something like a dog in the original sentences. In this case, one can see that the student was trying to translate the abstract sentences into concrete referents. Moreover, the student transcribed each sentence into its own box within the drawing.

Neither abstract representations, nor the condition of working in a dyad provided any reliable evidence of helping the students answer the questions. Abstract dyads (n=22) gave 47.7% correct answers to the questions based on the relational sentences compared to 50% for the non-abstract dyads (n=4). Abstract individuals (n=23) gave 50.2% correct answers compared to 31.5% for non-abstract individuals (n=16). There were no significant effects using these values or the values broken down by grade level. It should be noted that the influence of abstract representations on problem solving cannot be addressed through the design of this experiment; student characteristics could be an underlying variable that influenced both representational abstraction and problem solving. Moreover, the problems may have provided only minimal discrimination between levels problem-solving efficiency. Nonetheless, one can see that the construction of an abstract representation had a minimal relationship to short-term, problem-solving performance on this task.

Discussion

The dyads constructed abstract representations at a rate consonant with the expectations derived from the truth-wins model. Although the dyads did not exceed the model, this result is striking given the large body of prior research that has found little evidence that groups approximate this model. Moreover, as in Experiment 1, a higher overall rate of dyad abstraction occurred even though there were no instructions to develop abstract representations.

Because dyads matched the truth-wins model, one interpretation is that given a choice, the dyads “selected” abstract representations offered by individuals within the dyad. By this interpretation, dyads did not collaboratively construct abstractions but rather chose to use abstract representations if an individual brought up the idea. However, the fact that dyad problem-solving performance did not benefit from the abstractions diminishes the strength of this interpretation. An assumption of the truth-wins model is that groups have a rational basis for selecting the best answer within their midst (Thomas & Fink, 1961). Otherwise, they would have no *reason* to gravitate towards correct answers. However, because problem solving did not improve, it is not clear whether the “best answer” rationale for choosing abstractions could have been used by the dyads. An alternative interpretation is that the dyads selected abstractions from their members on the grounds that the abstractions helped resolve communicative demands. This is an interesting possibility because the rational basis for choosing an abstract representation was based on the constraints of social reality (cf. Festinger, 1950). The rationale for choosing an abstract representation was exclusive to the condition of working in a group, although the actual production of an abstraction still occurred within an individual regardless of group forces.

Another alternative interpretation is that the abstractions emerged from dyadic interactions regardless of potential rational justifications for any single representation that an individual brought to the group. According to this interpretation, dyad abstraction rates were prevented from exceeding the model due to a variety of factors described below. Although the frequency data do not support the rejection of the truth-wins model, incidental observations of the dyads suggested that negotiation played a role in the construction of the abstractions. For example, one dyad was working on a packet that described the effects of population changes throughout a food chain. One student had written, "less ferns --> less rabbits --> less wolves." The second student had written, "A = B + C." Upon noticing what they had each written, the second student asked where the ferns, rabbits and wolves had come from, as the problem did not indicate these things. Later, the first student asked the second student whether A was changing B or vice-versa. After some more discussion, the students developed the formalism, "A --> B --> C." In this case the dyad members combined the abstract aspects of one another's representations as a side-effect of negotiating the meaning of their respective representations. A second dyad provides an interesting example of how the meaning of a representation emerged through a process of negotiation. In this dyad, one student had drawn a picture of a monkey and a tree. To the left of the picture was the letter H with an arrow pointing ambiguously between the monkey and tree. The second student had also drawn a picture of two organisms side by side, although the relationship between the organisms was neither explicit nor implicit (e.g., which ate which). Upon looking at the first student's visualization, the second student asked whether the H was impacting the monkey or the tree. The first student stated, "The H is pointing to the monkey." Building on the first student's representation, the second student drew a picture of a banana with an arrow from the monkey to the banana. This caused some perplexity in the first student who had intended her original arrow to show that the monkey represented the letter H, not that H was transmitting to the monkey. After some further discussion, the dyads located the source of the confusion. Ultimately, they used letters instead of pictures, and used the transmission meaning of the arrow instead of the labelling meaning. Although neither had begun with an explicit representation of a directional transmission, its representation emerged as they came to understand one another’s meanings (cf. Pea, 1993). In each of these examples of group negotiation, one can see how the initially different representations, the mutual knowledge problems, and the need to represent structure jointly set the stage for developing a more abstract representation.

Given the preceding examples of representational negotiation, the failure to exceed the truth-wins model may have resulted from my selection of visualization materials. For example, the 9/10th grade individuals were able to construct abstract visualizations at such a high rate that it was impossible for the 9/10th grade dyads to exceed the truth-wins model even though every dyad constructed an abstract representation.[4] Considering both age groups, all the theoretical probabilities of dyad performance ranged between .84 and .99 (see Table 2). Although this result provides good testament to the individuals' abilities to construct abstract visualizations, it leaves very little room for revealing the emergence of abstractions in dyad problem solving. One explanation for the high level of abstraction in the individuals is that several of the packets in this experiment used visually unfamiliar referents like DNA and proteins. As a consequence, it would be difficult for individuals to develop non-abstract, concrete representations of the referents. In the following experiment, subjects worked on a visualization problem that involved visually familiar referents. As a consequence, individuals tended to draw pictures of the referents, whereas the dyads tended to make abstract visualizations.

EXPERIMENT 3

In this experiment, the students' task was to represent and answer questions about a paragraph of information that described the lake requirements of different fish. The following is a selection from the informational paragraph: *When either the Spotted Halluck or the Black Froling live in a lake, the lake has weeds. However, the Spotted Halluck needs a lake with trees around it, while the Black Froling needs a lake with minnows and a sandy bottom.*

The questions associated with the paragraph of information required indexing information by the fish or the lake attribute. For example, one question required finding whether two fish need a common lake attribute. Another question required finding out what lake attributes occur most often. Thus, given these questions, a useful representation includes two dimensions of information. A matrix is one such formalism that can separate the fish and the lake attributes so that the problem solver may focus on either. Although a matrix primarily includes verbal material, it is still a visualization in the sense that it is a non-linear organization of information.

The current experiment incorporated several methodological changes to Experiment 2. In Experiment 2 several of the packets used topics with unfamiliar referents. In the current study, problems included well-known categories of referents (i.e., fish and lake attributes) that were given visually descriptive names (e.g., *spotted* Halluck). This made it easier for students to make meaningful, non-abstract representations in which they draw pictures of each referent. At the same time, it satisfied the criteria for a mutual knowledge problem, because the specific referents were novel. A second modification was to use a single set of materials that was seen by all subjects. Although limiting the generality of the results, the use of a single set of materials alleviated counter-balancing problems and narrowed the sources of experimental error. The use of a matrix problem in which there were two dimensions of information was not motivated by considerations involving the dyad and individual contrast. Rather, it was used to get a sense of how 7th-graders would visualize information of a different structure than the transmission structure used in Experiment 2.

Only 7th-graders participated in the current experiment. Although delimiting the subject population to early adolescence may reduce the generality of the findings, the descriptive evidence of Experiment 2 showed that, with respect to making abstract representations, the 7th-grade dyads did not operate as closely to the truth-wins model as the 9/10th-graders. Because the first two experiments had already demonstrated that high-school students could match or exceed the truth-wins model, it was worthwhile to see if this level of dyad production could be generalized to 7th-grade dyads.

Because of the differences between the materials of this and the last experiment, the criteria for abstraction were necessarily different. Using the results of a pilot study, two categories were chosen to distinguish abstract and non-abstract visualizations. 1) *Non-Pictorial*. A visualization that portrays referents as they might actually look (e.g., a picture) is usually less abstract than a visualization that can convey relationships between referents without modeling their physical appearance. Thus, a non-pictorial representation was considered a reasonable indicator of a representation's abstractness. 2) *Separation of Attributes*. For the current set of materials, one might create a matrix representation that used pictures of fish and lake attributes along the axes instead of verbal labels. This is an abstract representation although it still contains pictorial elements. To account for this possibility, the second coding category captured whether subjects included a distinct dimension for lake attributes. For example, a pictorial matrix organizes information around the two dimensions of fish and lake attributes. Another example is an image that uses separate lakes for each habitat attribute. Each lake has a single attribute (e.g., trees) and includes all the fish that required that attribute. This is an abstraction in that it uses attributes as the primary dimension for organizing the information, rather than organizing the information as one would actually find it in the world -- fish in a lake with all the proper habitat features. Categorizing by attributes minimally reflects a nascent understanding of the underlying two-dimensional structure of the problem.

Method

Subjects.

Forty 7th-grade, Life Science students from a New York, suburban middle school consented to participate in the study as part of their regular class period.

Design.

The only contrast was between dyad and individual visualizations. Students were randomly assigned to dyad (n = 12) and individual (n = 16) conditions. A larger sample for the individuals was chosen because their performance serves as a baseline for calculating the truth-wins model probabilities.

Materials and Procedure.

A single work sheet had a brief description of game management, a paragraph describing a number of fictitious fish and their lake requirements, a space for a visualization, and five questions about the fish and their lake requirements. The procedure was identical to Experiment 2. All students finished within the 20 minute allotment.

[Figure 3 -- about here]

Results

Figure 3 indicates that when compared by either the non-pictorial criterion or the attribute criterion, the dyads constructed abstract representations over five times more often than the individuals. For the criterion of using a non-pictorial representation, 6.3% of the individuals made abstract visualizations compared to 66.7% of the dyads; $\underline{Z}$=3.39, n=28, $\underline{p}$<.01. Using the parametric, one-tailed test described in Experiment 1, dyad production of abstractions significantly exceeded the .121 probability that a dyad would have included at least one member who would have constructed an abstract representation working alone; $\underline{Z}$=2.99, $\underline{p}$<.01. For the criterion of using a separate attribute category, 12.5% of the individual visualizations were abstract compared to 66.7% of the dyad visualizations; $\underline{Z}$=2.96, $\underline{p}$<.01. The dyad performance again significantly exceeded the truth-wins model of 23.4%; $\underline{Z}$=2.3, $\underline{p}$<.05. If a visualization was required to have both abstract codings to be considered abstract, the results were equivalent to those found for the non-pictorial criteria.

[Figure 4 -- about here]

Two independent coders, blind to the source of each visualization, had perfect agreement excepting an uncodable visualization, shown as Figure 4f. To be conservative, this dyad visualization was coded as non-abstract on both criteria. Figure 4a was the only matrix representation out of the 28 visualizations. The table of Figure 4b collected the information for each fish into a single row. Although less structurally articulate than a matrix, it is abstract because it includes a column for attributes and is non-pictorial. In Figures 4c and 4d the students organized the information around the dimension of lake attributes. For example, in Figure 4d, a different lake is shown for each attribute (i.e., a lake with trees and a lake with weeds). Within each lake resided the different types of fish that required that particular lake attribute. This is abstract because the visualization did not depict the way these fish and lake attributes would actually be organized in the physical world, assuming that each fish only survives in a lake with all the necessary attributes. Accordingly, Figures 4c and 4d are both abstract with respect to structuring their representation explicitly around attributes. Figure 4d, which was the only example of this type of representation, is not abstract according to the non-pictorial criterion. Figure 4e was a common type of non-abstract visualization constructed by individuals and shows each fish pictured in its own lake.

As in Experiment 2, the influence of abstract representations on problem-solving performance cannot be assessed by this experimental design. Moreover, there was only one individual that constructed an abstract representation according to both criteria. This made it impossible to partial out the problem-solving effects of an abstraction from the effects of working in a dyad. Abstract dyads (n=8) correctly answered 57% of the questions and non-abstract dyads (n=4) were correct 45% of the time. The abstract individual (n=1) correctly answered 80% of the questions and the remaining non-abstract individuals (n=15) correctly answered 23% of the questions. The dyad versus individual contrast did not reach significance; $Z=1.43$, $n=26$, $p<.1$.

Discussion

The positive effect of dyads on the production of abstract representations was definitive in this experiment. For both measures of abstractness -- non-pictorial images and attribute categories -- the dyads created abstract visualizations at least three times more often than predicted by the truth-wins model. These results imply that something unique was occurring in the dyadic condition that could not be accounted for by examining equivalent individuals. The dyad that created the matrix in Figure 4a provided a particularly clear example of how the condition of multiple perspectives supports representational abstractions. When this dyad turned in its visualization, the experimenter asked the members how they came up with the matrix. One member stated, "He wanted to make columns and I wanted to make rows." To negotiate their two perspectives on the problem, they managed to come up with the matrix formalism that included both columns and rows.

Compared to Experiment 2, the frequency of abstraction among the individuals was quite low. This can be attributed in part to the visual familiarity students have with fish, trees, lakes, and so forth. A second probable cause is that the referents of the problem were spatially contiguous and did not involve temporal change. This makes it much easier to draw pictures compared to the problems in Experiment 2 in which the referents were in causal relations distributed across time and space.

GENERAL DISCUSSION

Three studies developed evidence that dyads are more inclined than individuals to construct abstract representations. Although there were no directives to construct abstractions, the dyads in each study made abstract representations significantly more often than individuals. This occurred whether the measure of abstraction was the induction of an abstract rule or the construction of an abstract visualization. In two of these studies, the gear study (Exp. 1) and the matrix study (Exp. 3), the dyads' spontaneous constructions of abstract representations were so frequent that they exceeded the truth-wins model of optimal group performance (Thomas & Fink, 1961). In this model, the probability that a group produces an abstract representation is calculated according to the probability that the group would include at least one member who would have produced an abstraction in isolation. Because dyads crossed this threshold of performance, it suggests that there was a cognitive interaction within the groups that did not occur within similar individuals working alone.

The favored explanation of these results is that the dyads engaged task demands that were unique to group work, and that these task demands afforded representational abstraction. To successfully talk about the problems, dyad members had to ensure they had a common representation of the problem referents. For example, in Experiment 1 oppositely facing students had to develop a way to ensure that left and right meant the same side for one another. The need to construct a common representation was particularly high in all the experimental tasks, because the problems were novel and did not immediately offer an external representation that could anchor discourse. These problem characteristics made it less likely that individuals began with identical perspectives on a problem. Consequently, in the process of ensuring common representations, dyad members had to resolve their idiosyncratic representations of the problem. In many cases, this negotiation process produced a representation that was unlike the representation that either individual would have had working in isolation. For example, in Experiment 2 one dyad member had initially used an arrow as a labelling device, and the other member had not used an arrow, or any other connective device. As the dyad members resolved their different representations of the problem, the function of the arrow evolved into an indicator of transmission. Finally, collaborative representations were often abstract, because they bridged the multiple views that dyad members often had on the problem structure. In Experiment 3, the structural bridging of the individuals' representations was highlighted by the two students who developed a matrix that could map into their respective preferences for columns and rows.

The generality of this explanation of the current results is necessarily speculative. There are several additional possible explanations. One possibility is that the act of verbalizing itself facilitated abstraction. By this account, the individuals would have constructed abstract representations more often had they been encouraged to talk aloud. Another possibility is that the dyads had more information processing resources at hand. For example, in the gear study, the dyads could partition the tasks of modeling and enumerating each gear. This load sharing may have unfettered the resources necessary for noticing the odd-even pattern in the gear motions. Further supplementing the resource advantages of multiple individuals, there may have been an increased motivation in the dyad condition that led to increased effort (Slavin, 1983). Yet another possibility is that the members of a dyad reinforced one another. For example, if individuals work as a team, they can strengthen one another's convictions. This strengthening might be enough to push tentative representations over the threshold of acceptability. Similarly, one member of a dyad may trigger ideas in the other individual. In this scenario, working in a dyad does not precipitate new ideas via a collaborative representation. Instead the dyad stimulates ideas that individuals already had, however implicit. This is an appealing model because it asserts that just as a group can inhibit individual production, it can also activate it. However, this account, the motivation account, and the information processing account do not provide transparent explanations for why there were strong, positive dyad effects for the current tasks that have not been found in other tasks. The effects of extra processing power, motivation and mutual reinforcement should not be isolated to tasks involving the construction of representations, and presumably would have manifested in prior experiments involving different tasks and dependent measures. Moreover, these accounts do not explain why dyads gravitated towards abstract representations as opposed to some other form of production.

There are three primary facets that together appear to differentiate the current tasks from the previous tasks used to compare groups and individuals. First, the problems were amenable to representation through abstraction. Each of the tasks explicitly involved reasoning about complex relationships that provided the raw materials from which students could build an abstract structure. Methodologically, it also provided a source of evidence on participant productivity that did not rely on efficiency measures or explicit directives.

Second, there was a strong mutual knowledge problem inherent in all the tasks. The configurations of the referents in the problems were neither conventional nor depicted. Additionally, the problems supported multiple initial perspectives and forms of representation. The lack of a common anchor and the possibility of multiple perspectives may have served as a catalyst for the negotiation of a suitable referential anchor. In contrast to the mutual knowledge problem inherent in the current tasks, consider a common concept attainment task used in group research (e.g., Laughlin & Shippy, 1983). In this task, subjects must infer the rule that determines a sequence of playing cards (e.g., alternating hearts and spades). In this situation, cooperating group members have minimal mutual knowledge problems, because the playing cards have conventional names and are known to be in everyone's view. As a result, there is no need to engage in processes that ensure mutual knowledge of the problem referents. This removes the task demand for the referential negotiation that is hypothesized to be one cause of the abstract representations found in the current studies.

The third task feature that appeared to play a strong role in the current results was the possibility of mediating problem solving through a visualization. At the same time that the problems of mutual knowledge engaged the processes of collaborative construction, the visualizations facilitated their success. The visual representations, whether gestural or on paper, served as a focal point for coordinating further discussion and negotiations (Jones & Vroom, 1964). In a separate set of studies, Schwartz and Black (1992) demonstrated the special benefit of visual anchors for groups. In these studies, adolescent dyads and individuals solved transmission problems similar to those described in Experiment 2. Students in both conditions were shown how to construct directed graphs to solve these problems. The dyads and individuals then solved additional transmission problems in the conditions of using experimenter prepared path diagrams, constructing their own, and working without any visual support. The results showed that the visualizations, whether jointly constructed or supplied by the experimenter, enhanced the performance of the dyads significantly more than they enhanced the performance of the individuals. In the current studies dyads may have been able to move their joint cognitions forward, because they could construct a visual anchor.

Further research will be necessary to determine whether the highlighted task demands and problem characteristics were generally responsible for the high frequency of group abstractions. One research approach is to manipulate the proposed task demands and features. There are three primary lines of manipulation. First, one could regulate the level of mutual knowledge group members could assume. For example, one could control the novelty of a problem or the access to shared external reference. Second, one could vary the diversity of perspectives individuals bring to a group task. For example, one could employ a jigsaw approach in which individuals develop different vantages on a problem prior to working on the problem within a group. Third, one could vary the opportunities and supports for representational negotiation. For example, one could manipulate the opportunities for constructing visual representations.

A second overall approach, complementary to the experimental approach, is to develop fine-grained interactional analyses that document the processes and products of representational negotiation. This was impossible in the last two experiments reported here, because of a concern from the first experiment involving the use of recording devices. This concern was that videotaping might have introduced an unwanted advantage to the dyads, if one assumes that children working alone may be more intimidated by a videotaping protocol than dyads. Consequently, I decided to run the experiments in a regular classroom setting to remove this potential confound in the dyad and individual contrast. However, work by others, not focused on a group versus individual contrast, has shown that an interactional analysis can illuminate the process of constructing a collaborative representation. For example, Roschelle (1992) showed that convergent conceptual change occurred in turn-taking cycles in which group members developed progressively higher standards for the sharing of evidence. Studies like this could provide valuable evidence on the mechanics of collaborative construction. I suspect that interactional studies would find numerous forms of negotiation depending on the individuals' knowledge and the affordances of the task at hand. For example, in Roschelle's work subjects had access to external sources of feedback (i.e., a computer simulation). This was not the case in the current studies (except for the binary feedback of the gear study). Consequently, it seems unlikely that a collaborative construction of empirical, evidential acceptability would occur. Moreover, as found in the gear study, representational negotiation can operate at the implicit level of modifying hand gestures. The mechanisms of this negotiation may be quite different from other forms of representational negotiation. Although the process and products of representational negotiation may take numerous forms, I believe that careful attention to the conditions preceding a period of representational negotiation will reveal strong evidence for the important role of mutual knowledge problems in the co-construction of representations.

Instructionally, the current work may augment research on cooperative learning (e.g., Johnson & Johnson, 1987; Slavin, 1983) by indicating one situation in which it is particularly advantageous to use groups -- when the target concept is an abstraction such as a symbolic visualization. The natural response of groups to the demands of collaborative work could lead students to construct abstract representations that more closely approximate the representational conventions that are currently used (DiSessa, Hammer, Sherin & Kopakowski, 1991). Underlying this prescription is the assumption that having students generate or construct representations is better in the long run than just giving students ready-made representations (Bransford, Franks, Vye & Sherwood, 1989; Harel & Papert, 1991;

Schwartz, 1993). An important question is when the potential benefits of a constructivist pedagogy would extend to groups. For example, problem-based learning aproaches in medical school make extensive use of small groups that construct models of patients' interacting systems (Koschmann, Myers, Feltovich & Barrows, 1994). One might ask under what conditions of group construction do members of groups like these show the highest levels of transfer once they have left the group setting (Barron, 1992)?

With respect to final performance, there is an ambiguity as to whether instruction that relied on a group abstraction effect would benefit problem solving. The evidence from the first study showed how abstraction improved efficiency in the gear task. However, the last two studies suggested a minimal impact of abstract visualizations on problem-solving performance. This result may seem surprising for the dyads. One would expect that the successful negotiation of a collaborative representation would further communication, and therefore yield better problem-solving performance. However, there are a number of factors that could have led to the null results including the discriminability of the problems used to test performance. One likely factor is that many of the abstract visualizations were original creations. This novelty may have made the visualizations more prone to misuse, and thereby counter-acted their potential benefits. For example, many dyads omitted information in their visualizations or misread their own visualizations in answering the problems. It would be interesting to examine the long term effects of collaborative representations on dyad problem solving. Presumably, the dyads would become more facile in the construction and problem-solving uses of their constructions.

The strongest educational implication of the current work does not involve the potential transfer of representations or final problem-solving performance. Rather, it involves the construction of shared representation. In many domains of endeavor, there are no standard solutions or representations for a problem. In these situations, one must create a representation. It is here that group work can payoff by producing a more abstract and structured representation than those of individuals. Moreover, the resulting shared representation can anchor further meaningful discourse. These results will most likely occur when individuals within a group attempt to negotiate their representations of a situation. However, the co-construction of representation is not always the preferred solution to mutual knowledge problems. For example, in a didactic classroom mutual knowledge problems are often resolved by more precise definitions and examples on the part of the instructor. In a sense, this may be thought of as the "truth wins" or "most competent member" model of group instruction, with the teacher being the most competent member of the group. In the case of well-defined conventions and educational objectives this may be acceptable. Although I suspect, that like the history of research on group and individual comparisons, group performances will always fall well-short of the most competent member if there is not a co-construction of representation. But, regardless of the value of the didactic or collaborative approaches for imbuing conventional knowledge, there are many cases where the target knowledge state is not known by either party in a group. For example, the correct way to "think" about complex problems may not be known to the teacher or student, although both have their own explicit or implicit views on the matter. In a situation like this, an attempt to assess and negotiate differences in perspective could result in a shared construction of complex problem solving. Minimally, this shared construction should further communication. Maximally, it may result in a representation of complex thinking that neither teacher nor student would have thought of alone.

CONCLUSION

In two of the current studies, abstract representations emerged from group work in the sense that they could not be accounted for in terms of the work that similar individuals produced in isolated but otherwise identical situations. The source of the dyads' representations was thus distinct from the source of the individuals' representations. A theoretical stance consonant with this result should allow for the social emergence of knowledge. Such a theory would have a different orientation from theories that focus on the communication of pre-existing knowledge. The question is not how individuals become a member in a larger cognitive community as in apprenticeship studies (e.g., Rogoff, 1991). Rather, the question is how a cognitive community could emerge in the first place.

A theory that supports the social emergence of knowledge should allow that groups operate under rational constraints that may not be available to individuals. For example, the truth-wins model assumes that the rationality available to individuals and groups is the same. Groups choose the best answer from the members' contributions on the same grounds that individuals would choose the answer if it were available to them. If one accepts that the construction of abstract representations in groups was the result of rational behavior, then the fact that groups exceeded the truth-wins model suggests that the groups had a rational basis not equally available to individuals (e.g., communicative constraints). An example of a group rationality that exists separately from individual rationality is found in the work of Clark and Wilkes-Gibbs (1985). According to the "Principle of Least Collaborative Effort," an individual's cognitions can be regulated by a rationality exclusive to group functioning. These researchers showed that individuals sacrificed their own linguistic expediency to ensure the overall optimization of future group communications. For example, individuals exerted extra effort to establish economical referring expressions for the group by incorporating their partner's language. While this increased an individual's effort, it reduced the overall group effort. Thus, individual cognitions were guided by the information processing needs of the group as a whole. Although one can think of non-information processing reasons for increasing personal effort (e.g., a politeness constraint), the principle represents an example of how cognitive activity is regulated by a group rationality that presides over individual rationality.

The current results provide an existence proof for the emergence of cognitive products in group work. Like others (e.g., Freyd, 1983), I have argued that specific task demands associated with communication introduce affordances for the emergence of a distinctive form of representation -- abstraction. In other terms, group cognition follows a rationality that is distinguishable from the rationality that guides individual cognition. There are two classes of theory that fit this argument. One class posits that individuals and groups have essentially the same cognitive processes or operators. It is the structure of the social environment that leads to the different results of identical processes in group and individual work. Supporting this theory, one might note that the same cognitive activities that occur within groups can occur when working alone, as in the case of taking multiple perspectives on an issue, or when trying to negotiate the meaning of a complex journal article. The other class of theory takes the opposite approach by claiming that group and individual cognitions have different processes. In these theories, group cognition has a being that is distinct from individual cognition. Such a theory has precedent in Durkheim's construct of the "conscience collective" (Durkheim, 1972), and is re-emerging with the development of the idea of distributed intelligence (Salomon, 1993). These theories posit that the unit of psychological analysis for group cognition occurs at the level of the group and cannot be adequately located in any individual. In a sense, the group has a mind. This class of theories can respond to the ability of isolated individuals to carry out group-based cognitions, such as taking multiple perspectives, by arguing that individuals are internally simulating a slice of group cognition. As an analogy, the fact that people can imagine the physical behaviors of distal objects does not mean that their minds embody the laws that yield these physical behaviors. Similarly, just because individuals can simulate the rationality of groups, this does not mean that they necessarily embody this rationality. An interesting implication of this class of theory is that individuals' attempts to simulate socially based cognition may be prone to misconceptions, paralleling the case of naive physics (McCloskey, Caramazza & Green, 1980). In any event, although the two classes of theory have deep differences, it is clear that they, and the current results, demand a consideration of the special nature of socially situated cognition.

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Table Captions

Figure Captions

	Eventually Induced Rule			**Never Induced Rule**			**Total Averages**		
	Secs[a] (SD)	p(correct)[b]	n[c]	Secs	p(correct)	n	Secs	p(correct)	n
Individuals	32.2 (16.3)	.67	2	19.2 (12.9)	.79	12	21.1 (13.5)	.77	14
Dyads	15.7 (8.5)	.96	7	29.5 (26.6)	.80	5	21.5 (18.7)	.90	12
Total Avg.	19.4 (11.8)	.90	9	22.5 (17.7)	.79	17	21.3 (15.7)	.83	36

[a] Per problem.

[b] Probability of a correct first answer to a problem. (Second answers were always correct.)

[c] Number of dyad or individual means used in averages.

Table 1

	7th Graders			9/10th Graders		
	Individuals (n=20)	Expected Dyad	Actual Dyad (n=16)[a]	Individuals (n=19)	Expected Dyad	Actual Dyad (n=10)
NO SEMANTICS	.75[b]	.94[c]	.88[b]	.89	.99	1.0
NO TRANSCRIPTION	.60	.84	.75	.68	.90	1.0
UNIFIED LINKS	.80	.96	.69	.79	.96	1.0

[a] Number of dyads (not individuals).

[b] Empirically found probability.

[c] Probability of a dyad having at least one individual who would have used this indicator of abstraction.

Table 2.

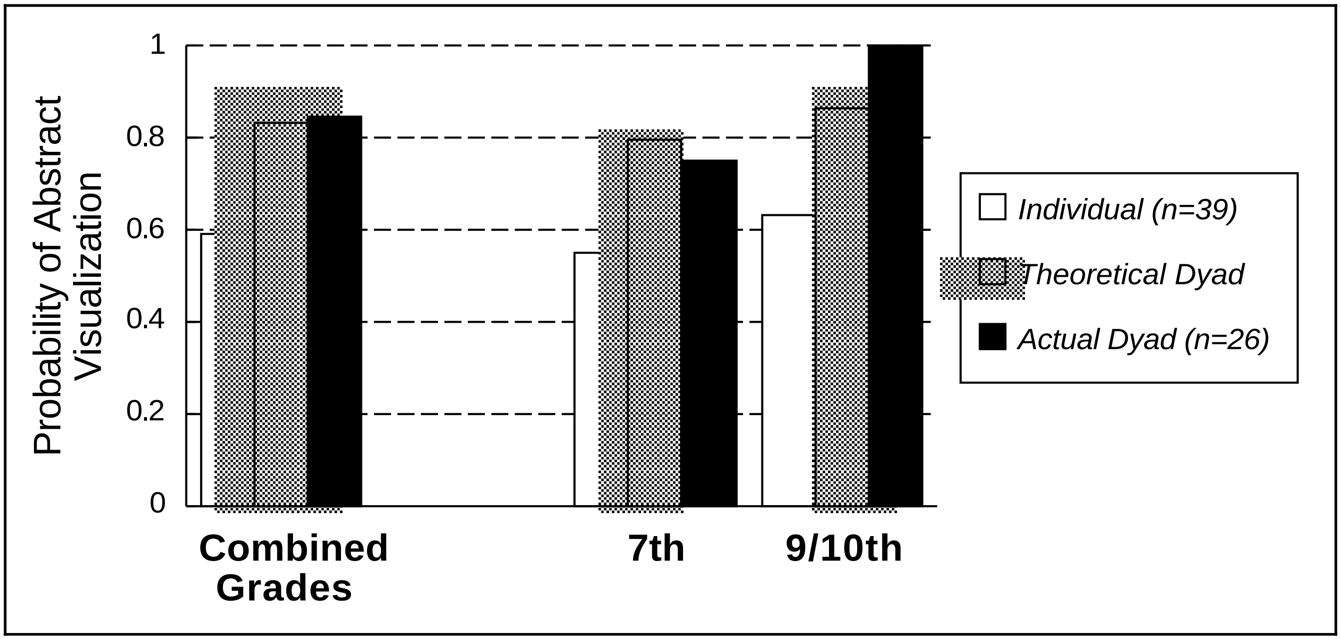
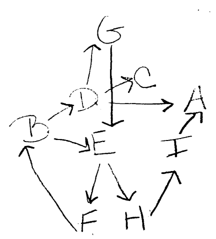
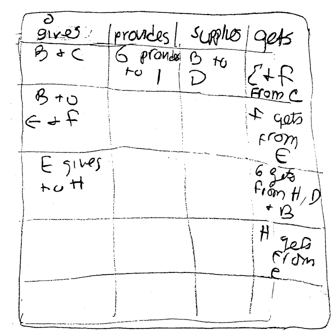

Probability of Abstract Visualization
1
0.8
0.6
0.4
0.2
0
Combined Grades
7th
9/10th
Individual (n=39)
Theoretical Dyad
Actual Dyad (n=26)

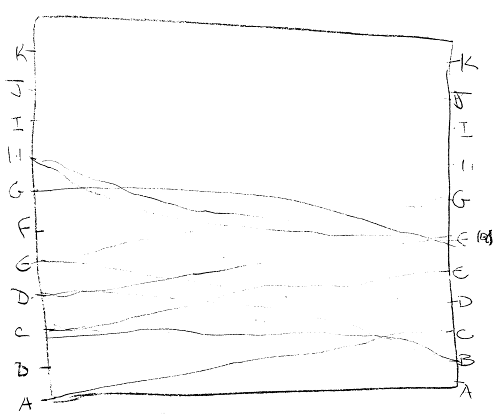
Figure 1

Abstract	Non-Abstract

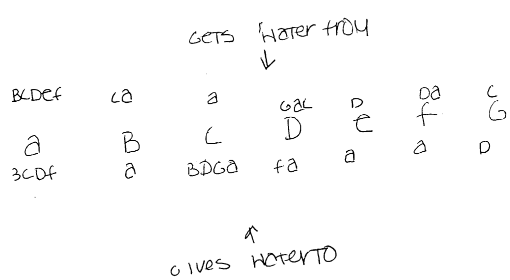
(a)



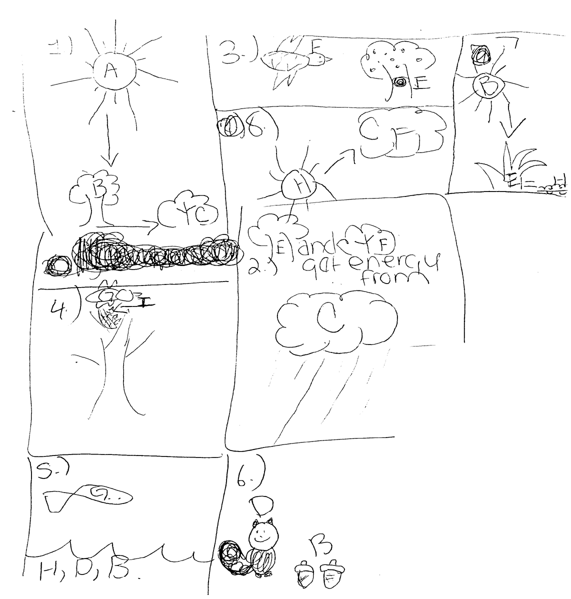


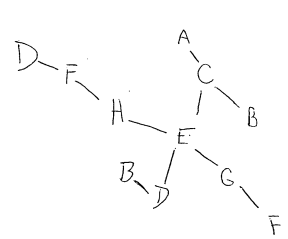


B = DE
D = C
G = D
E = H + F
B = F
H = I + A
A = D
E = G



(g) Semantics & Sentence Transcription





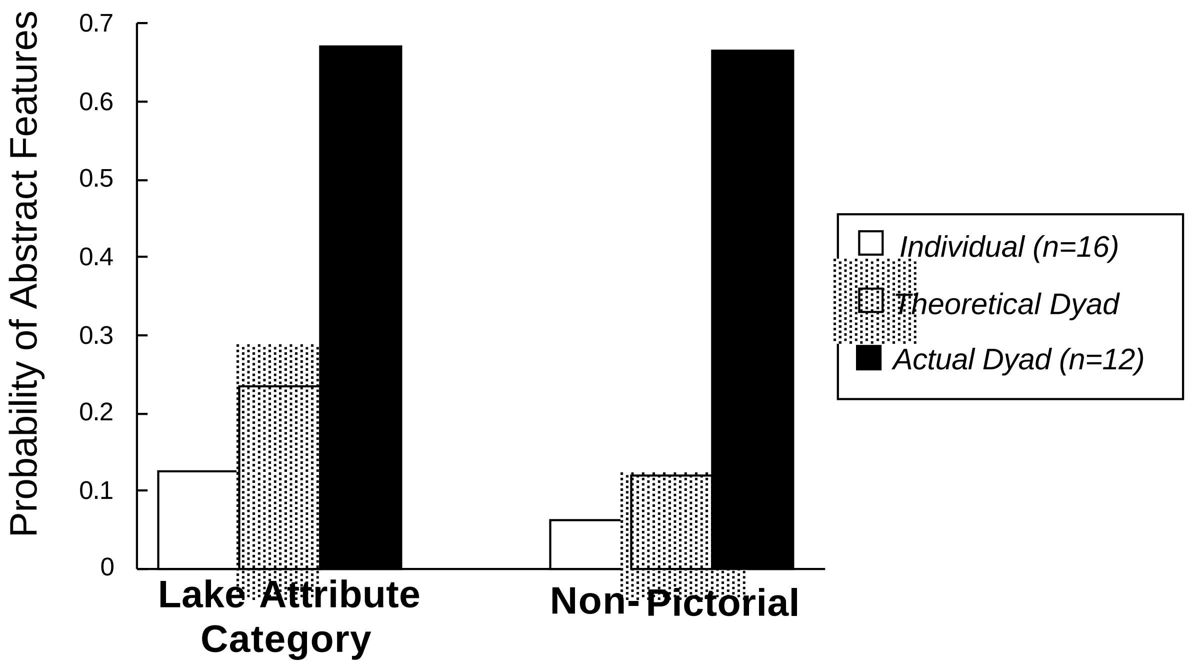
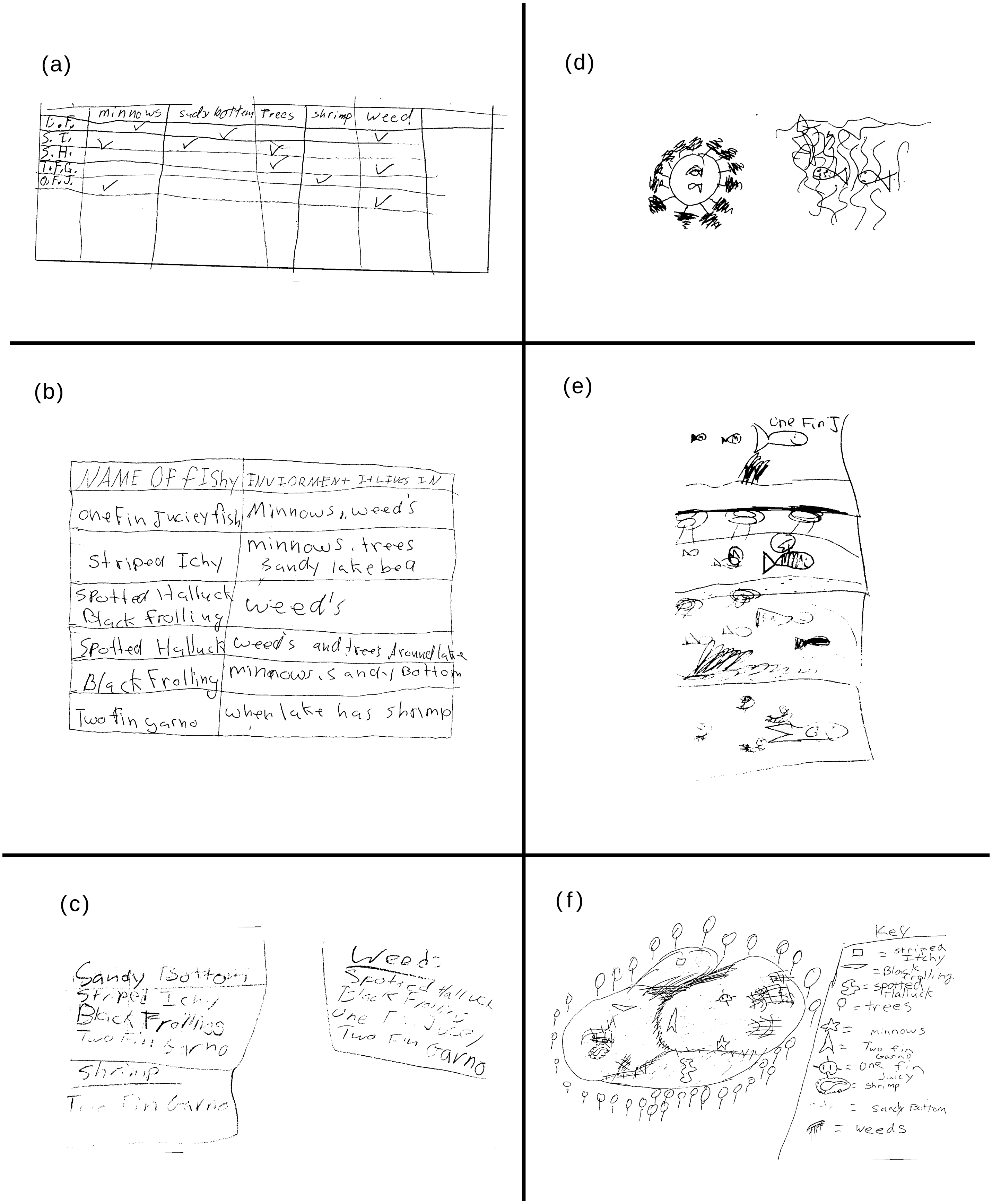

Probability of Abstract Features
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Lake Attribute Category
Non-Pictorial
Individual (n=16)
Theoretical Dyad
Actual Dyad (n=12)

Figure 3


(a)
minnows
sandy bottom
Trees
shrimp
weed
D.F.
S. I.
S. H.
T.F.G.
O.F.J.
(b)
NAME OF fIShy
ENVIORMENT IT LIVES IN
oneFin Juciey fish
Minnows, weed's
striped Ichy
minnows, trees sandy lake bed
Spotted Halluck Black Frolling
weed's
Spotted Halluck
weed's and trees Around lake
Black Frolling
minnows, sandy Bottom
Two fin garno
when lake has shrimp
(c)
Sandy Bottom
Striped Ichy
Black Frolling
Two Fin Garno
Shrimp
Two Fin Garno
Weeds:
Spotted Halluck
Black Frolling
One Fin Juicy
Two Fin Garno
(d)
(e)
One Fin J
(f)
Key
= striped Itchy
= Black Frolling
= spotted Halluck
= trees
= minnows
= Two fin Garno
= One fin Juicy
= shrimp
= Sandy Bottom
= weeds

Footnotes

[1] The probability that a dyad includes at least one member who could have the solved the problem in isolation is found by calculating the probabilities of all the possible couplings of successful and unsuccessful individual problem solvers. For example, imagine that individuals have exhibited a .2 probability of correctly solving a problem and one is interested in finding the theoretical probability of success for dyads. One coupling would be that individuals A and B can both solve the problem (.2 x .2 = .04). Thus, for any given dyad there is a .04 probability that both dyad members would be able to solve the problem in isolation. A second coupling is if A can solve the problem but B cannot (.2 x .8 = .16). A third coupling is if A cannot solve the problem but B can (.8 x .2 = .16). The final possible coupling is if neither member of the dyad could solve the problem (.8 x .8 = .64). The probabilities of the first three couplings, in which the dyad would include at least one member who can solve the problem, sum to .36. Thus, there is a .36 probability that at least one member of the dyad will be able to solve the problem. If dyads are operating rationally by following the correct individual(s) within each dyad, then one should expect 36% of the dyads to get the correct answer. Usually, dyads fall below this level of performance, presumably due to process losses within the dyad.

[2] The statistical method calculates all possible combinations of individual probabilities and does not require a Z-score (Lorge & Solomon, 1955, p.142).

3. If the induction of a parity rule were contingent on problem-solving performance, it would necessitate a substantially more complex model for

determining the optimal, expected dyad performance (see *Model B*, Lorge & Solomon, 1955; *Egalitarian Model*, Restle & Davis, 1962). As a simplified example, imagine that those individuals who solved the problems without error had an 80% induction rate and those who made errors had a 30% induction rate. According to the truth-wins model, a dyad has a .96 probability of inducing the parity rule if it made no errors, and a .51 probability of inducing the rule if it did make errors. Next imagine that 40% of the individuals solved the problems without error. According to the truth-wins model, this means that a dyad has .64 probability of solving the problems without error, and a .36 probability of making errors. Consequently, there is a .614 probability (i.e, .64 x .96) that a dyad solves all the problems correctly <u>and</u> induces a parity rule, and there is a .184 probability (i.e., .36 x .51) that a dyad does not solve all the problems correctly <u>and</u> induces a parity rule. Therefore the overall probability of dyad rule induction is .798 (i.e., .614 + .184). If one had simply used the individual rate of induction, which was 50% in this scenario, the expected probability of induction would have only been .75.

[4.] The high level of performance of the 9/10th graders as compared to the 7th graders may have been the result of the older students' extra exposure to abstract visualizations as might be found in discussions of the nitrogen, carbon, and water cycles in a Biology class.