When Diversity in Training Improves Dyadic Problem Solving

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Summary: Students learned how to solve binomial probability problems from either a procedurally based lesson or a conceptually based lesson and then worked in distributed pairs by using a computer-based chat environment. Cognitively homogeneous dyads (i.e. both members received the same lesson) performed more accurately on standard problems, whereas cognitively diverse dyads (i.e. each member received a different lesson) performed more accurately on transfer problems. The cognitively homogeneous dyads perceived a greater sense of common ground with their partner, but spent a greater proportion of their time communicating about low-level details (e.g. message verification) whereas the cognitively diverse dyads spent a greater proportion of their time on high-level discussion (e.g. solution development). Results help to clarify that common training leads to more positive perceptions of collaboration, but only improves performance on problems that are highly similar to those experienced during training, whereas diverse training improves the ability of a dyad to perform well in new situations. Copyright © 2011 John Wiley & Sons, Ltd.

INTRODUCTION

Problem-solving groups are ubiquitous in daily life and are especially popular in the workplace or other organizational settings (Salas & Fiore, 2004) and in the classroom (Dillenbourg, 1999; Webb & Palincsar, 1996). A problem-solving group consists of two or more people who work together, either in person or virtually, to solve a problem. People work with others for a number of intuitive reasons including distributing workload, increasing the pool of knowledge, and checking against the commission of errors. Critical work occurs in groups in a wide variety of applied contexts such as medicine (Patel, Cytryn, Shortliffe, & Safran, 2000), ship navigation (Hutchins, 1995), aircraft and spacecraft operation (Orasanu, 2005), emergency response (Pfeifer, 2007), and scientific research (Dunbar, 2001). Working with peers in small groups is also used frequently to support student learning of academic content, especially mathematical problem solving (Barron, 2003; Roschelle & Teasley, 1995; Vye et al., 1997).

Much of the cognitive research tradition on problem solving builds on the influential work of Newell and Simon (1972) who modeled the individual as an information processor who engages in problem representation and solution processes. Within the group cognition literature, researchers are beginning to conceptualize groups as information processing units themselves, with information processes that go beyond the capacities, activities, or representations of the individual group members (Curseu & Rus, 2005; Goldstone, Roberts, & Gureckis, 2008; Hinsz, Tindale & Vollrath, 1997; Hutchins, 1995; Tindale & Sheffey, 2002). For instance, in addition to each individual’s own representation, a group needs to develop a shared problem representation or mental model for the problem or task. Sharedness refers to a pre-existing representational context that becomes shared among group members whereas emergence refers to new common cognitive structures that are invented through group interaction (Curseu, 2006; Goldstone et al., 2008; Schwartz, 1995). Through interaction, new representations may become richer than were any of the individuals’ initial problem representations (Moreland & Levine, 1992). Emergent aspects of group interaction, where the combination of individual contributions leads to superior products or processes, are of most interest both theoretically and practically (Hinsz, et al. 1997; Shiflett, 1979; Stein, 1972). Yet, although many believe that working with others can improve cognitive performance, this has rarely been found to be the case in empirical laboratory studies (Dennis & Valacich, 1993; Kerr & Tindale, 2004). More research is needed in order to determine when, how, and under what conditions working with others can improve problem-solving performance.

The goal of the present study was to contribute to our understanding of how the composition of a small group in terms of cognitive diversity influences problem-solving performance. We use the term cognitive diversity to refer to qualitative differences in the kind of knowledge possessed by dyad members. Instead of focusing on differences in the quantity of knowledge or status (e.g. high-knowledge versus low-knowledge, or expert vs. novice status), we manipulate the training that each dyad member receives in order to instill different but complementary kinds of knowledge about how to solve problems. This kind of diversity is similar to the construct called information diversity as defined by Williams and O’Reilly (1998) and variety as defined by Harrison and Klein (2007). The present manipulation was intended to promote diversity in the variety of perspectives or knowledge represented among members of a group, rather than diversity as a mechanism for invoking disparity or separation. As compared with other kinds of diversity in group composition (such as demographic characteristics of gender or nationality, or personality profiles), little research has been focused on the effect of cognitive diversity on group performance (Curseu & Rus, 2005; Harrison & Klein 2007; Horwitz & Horwitz, 2007; Mannix & Neale, 2005; van Knippenberg & Schippers, 2007).

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The main question addressed in the present study is whether instilling cognitive diversity as a function of training will improve or degrade group problem-solving performance. On the basis of aspects of existing research on group diversity (e.g. Gigone & Hastie, 1993; Standifer & Bluedorn, 2006; van Knippenberg & Schippers, 2007), we examine two opposing theoretical approaches, which we refer to as common ground theory and group synergy theory. We use the term common ground theory to refer to the idea that homogeneous dyads (whose members have been trained in the same way) will communicate more effectively and form shared representations of the problems that they are solving more easily than diverse dyads. These advantages in communication should lead to better performance by homogenous dyads. In contrast, we use the term group synergy theory to refer to the idea that cognitively diverse groups have a broader and more varied knowledge base that will allow for the generation and analysis of more alternative solution plans. This should allow diverse dyads to perform more successfully than less diverse groups. Given the opposing predictions of these two approaches, the current experiment has important theoretical implications.

Possible Benefits of Cognitive Homogeneity

Many empirical studies have demonstrated advantages for homogeneity on group performance (i.e. Cannon-Bowers, Salas, & Converse, 1993; Stout, Cannon-Bowers, Salas, & Milanovich, 1999). A prevailing explanation for these findings refers to a group’s ability to easily establish a shared representation of the problem-solving task and to communicate more effectively. Researchers have suggested that group members with different backgrounds may represent and process information differently and that this may contribute to inefficiencies in group performance as a whole (Curseu & Rus, 2005; Paulus, 2000). Hinsz et al. (1997) further elaborated on this point and focused on the obstacles that diverse groups may face as they attempt to create the shared mental model for the group: ‘Group members with unshared and dissimilar representations are expected to disagree on the nature of the situation or problem...and achieve suboptimal levels of performance and effectiveness’ (Hinsz et al., 1997, p. 45).

Further, diversity among group members may also incur more negative impressions of group members or of group performance and less satisfaction in the group process (Curseu, Schruier & Boris, 2007). This hypothesis can be derived from a related line of research on group decision making in which small groups routinely show a preference for discussing only information that is shared by a majority of group members. When groups tend to focus on information that is common to the group, members evaluate each other as more competent, knowledgeable, and credible than when they discuss much unshared information (Wittenbaum, Hubbell, & Zuckerman, 1999). This phenomenon has been referred to as a mutual enhancement effect, and one explanation that has been offered for it is that the discussion of shared information is positively reinforced. Wittenbaum suggested that discussing only shared information eases the interaction by helping members relate to one another. In addition, she found that members who communicate shared information receive more positive evaluations from other members for doing so. Moreover, recipients of shared information feel better about their own task knowledge when another member’s view reinforces their own. Thus, we would expect that the homogenously trained dyads in our study would experience the mutual enhancement effect more so than the diverse dyads.

In summary, negative effects of cognitive diversity on problem solving may occur because of the likelihood that homogeneous groups will more easily form a shared representation of their task than diverse groups. However, there has been little empirical work establishing the link between homogeneity among members, communication patterns, perceptions of the working relationship, and the quality of shared problem representations (Kerr & Tindale, 2004). In particular, a common ground approach predicts that homogeneous groups should be more efficient in their communication. As a result, homogeneous dyads should not need to engage in as much low-level communication, which in turn will give these groups the opportunity to engage in more abstraction, reflection, and higher level solution planning. Homogenous groups should also hold more positive perceptions of each other and group performance and should outperform diverse groups on problem-solving tasks. The present research provides a direct test of these predictions.

Possible Benefits of Cognitive Diversity

Although diversity among group members has been seen as a liability in the studies discussed above, a recent review has suggested that diversity along cognitive dimensions, or deep level diversity, could help group performance in some situations (Horwitz & Horwitz, 2007). A few studies have been able to demonstrate that groups high in cognitive diversity may experience advantages in problem solving (Maznevski, 1994; Ohtsubo, 2005; Stroebe & Diehl, 1994: Wiley & Jolly, 2003). In Stroebe and Diehl (1994), four-member groups were asked to generate as many ideas for ways to protect the environment as they possibly could. Cognitively diverse brainstorming groups (with different types of specialized knowledge) generated more ideas for protecting the environment than did the more homogenous groups. Using another creative problem-solving task, Wiley and Jolly (2003) found that cognitively diverse dyads were more effective than more homogenous dyads at finding a remote associate that formed a meaningful phrase with sets of three stimulus words. Ohtsubo (2005) examined the effects of diversity on the solving of logic puzzles. In this study, diversity in knowledge was manipulated by either giving all members of a triad the same knowledge of all of the clues needed to solve logic puzzles (the homogenous condition) or giving each member a different subset of the clues necessary to solve the puzzles (the diverse condition). Cognitively diverse triads solved the puzzles better than the cognitively homogenous triads. Finally, in relation to collaborative problem-solving activities meant to support learning, Wiedmann, Leach, & Wiley (accepted) have found that triads with diverse math ability perform better in a learning-by-invention problem-solving activity where they are asked to invent a formula for standard deviation.

As demonstrated by these research studies, cognitive diversity can have a positive effect on performance for some problem-solving tasks. Explanations for these effects have been offered in terms of two main factors. First, more diverse
groups have a broader knowledge base to draw upon than do more homogeneous groups (Curseu & Rus, 2005; Hinsz et al., 1997; Ohtsubo, 2005; Wiedmann et al., in press; Wiley & Jolly, 2003). That broader knowledge base itself aids in the activation of a broader range of ideas among group members. In addition, interaction among individuals is thought to yield additional positive effects. During idea generation, an idea proposed by one group member can activate related knowledge in another group member; this in turn can lead to a new idea being generated by the second group member. In this way, a synergistic effect is created whereby one set of ideas proposed leads to the generation of more ideas. As the more diverse groups should have a wider range of ideas from which to draw upon, there should be a wider range of knowledge activation within the individual members, which in turn leads to more idea generation (Curseu, 2006; Hinsz et al., 1997; Paulus, 2000; Salazar, 1995). These beneficial aspects of group interaction on idea generation have been referred to as positive synergy effects (Baruah & Paulus, 2009; Larson, 2007).

A second way in which cognitive diversity may improve problem solving is attributable to the need for members with different backgrounds to explain and negotiate their understandings in order to reach a shared representation (Moreland & Levine, 1992). The presence of alternative solutions to a problem within a group may also prompt more evaluation of each group member’s suggestions (Wiley & Jensen, 2006). Although additional processes of negotiation, evaluation, and explanation may make problem-solving performance on routine problems less efficient, the extra effort spent negotiating representation and solution strategies may actually lead to the emergence of more robust, conceptual, or abstract understanding of the task domain (Barron, 2003; Schwartz, 1995; Webb, Troper & Fall, 1995; Wiedmann et al., in press; Wiley & Jensen, 2006). Thus, cognitive diversity and conflict could actually make the group more effective at problem solving, and in particular, these groups may be more flexible at solving future problems that do not closely match the surface features of the problems they were instructed on.

In summary, group synergy theory predicts that cognitively diverse groups will have a broader and more discrepant knowledge base that will afford the generation and analysis of more alternative problem solution plans, which could lead to better problem solutions. The presence of more cognitive diversity should also lead to better problem-solving performance particularly on new problems that require participants to extend beyond their explicit training. The present study provides a test of these predictions.

The Current Research Study

In order to test the predictions of group synergy and common ground theories, we investigated dyads whose members had been asked to solve binomial probability problems such as ‘If a coin is flipped five times, how many different sequences would contain two heads and four tails?’ On the basis of earlier research (Mayer & Greener, 1972), some students were taught using a method that emphasized the calculation of the formula (i.e. procedural instruction) whereas other students were taught using a method that emphasized the meaning of the variables in the formula (i.e. conceptual instruction). To manipulate the diversity of training in this study, for some dyads, each member received a different instructional lesson (i.e. one received procedural instruction and one received conceptual instruction) whereas for the remainder of the dyads, both members received the same instructional training (i.e. both received conceptual instruction or both received procedural instruction).

The differences between procedural and conceptual learning in the field of mathematics has been well established in a wide array of research studies (Baroody, 2003; Byrnes & Wasik, 1991; Canobi, Reeve, & Pattison, 2003; Rittle-Johnson, 1999, 1991; Canobi, Reeve, & Pattison, 2003; Rittle-Johnson, Siegler, & Alibali, 2001). Procedural learning is characterized by an emphasis on learning sequences, step-by-step procedures, or the computation of formulas for solving problems. This type of instruction provides the learner with the knowledge of ‘how-to-do-it’ (Kieras & Polson, 1985). In the current research, this type of training began by presenting the participants with the formal statement of a formula and then provided a step-by-step procedure on how to compute the formula (Mayer & Greener, 1972). Conceptual learning is characterized by emphasis on the underlying principles that relate to a particular domain such as binomial probability, and the understanding of the meaning and role of the variables in the formula. This type of instruction provides the learner with the knowledge of ‘how-it-works’ (Kieras & Polson, 1985). In the current study, this type of instruction used lessons that began by relating the components of the formulas to concrete instantiations, using examples from dice rolls (Mayer & Greener, 1972). While these two types of learning may represent two extremes of a continuum, they also represent two types of knowledge (Rittle-Johnson & Alibali, 1999).

The current research project compares the performance of problem-solving dyads composed of members who have equal access to skills needed to solve the problems, but who differ in the way in which they are trained to solve the problems. This is the first study to explore the effects of cognitive diversity on group problem solving in this way. Also, importantly, effects of diversity on group interactions are examined, and performance is measured on both problems that are similar to the ones used in instruction, as well as on transfer problems that require the application of problem-solving skills in a new way. Because the conditions that afford better transfer to new problem-solving situations are often different from those that support better performance on problems that are more similar to those encountered during practice, the use of both kinds of problem types is critical for understanding the contexts under which cognitive diversity may help and hurt performance.

As stated above, this study tests the opposing predictions of group synergy theory and common ground theory. On the basis of group synergy theory, we would predict that (i) cognitively diverse dyads should be more successful in solving problems (particularly transfer problems) than cognitively homogeneous dyads and (ii) that the presence of alternative perspectives will prompt cognitively diverse dyads to spend a greater proportion of their communications on high-level discussion of solution planning as compared with the cognitively homogeneous dyads.

In contrast, common ground theory refers to the idea that homogeneous dyads (whose members have been trained in the same way) will form shared representations of the problems that they are solving more easily than the diverse dyads. This should lead to better performance by the homogeneous dyads, because
they will communicate more effectively with their problem-solving partner. As a result, homogeneous dyads should not need to engage in as much low-level communication which in turn will give these groups the opportunity to engage in more abstraction, reflection, and higher level solution planning. On the basis of common ground theory, we would predict that (i) cognitive homogenous dyads should be more successful in solving problems than cognitively diverse dyads and (ii) cognitively homogeneous dyads should be able to spend a greater proportion of their communications on high-level discussion of solution planning as compared with the cognitively diverse dyads. Additionally, members of homogeneous dyads should have more positive impressions of their interactions than diverse dyads. Table 1 shows a summary of descriptions of group synergy and common ground theories, and their corresponding predictions on performance and communication.

**METHOD**

**Participants**

One hundred and twenty participants were drawn from the Psychology Subject Pool at the University of California, Santa Barbara, which is comprised of 800–1000 students enrolled in Introductory Psychology courses. Forty participants served in each of the three treatment conditions and were arranged into 20 randomly paired dyads (homogeneous-procedural, homogeneous-conceptual, and diverse). Dyads were neither existing teams nor friends. The pairings were *ad hoc* for the purpose of the experiment and were anonymous to limit prior familiarity. Six additional dyads were run to replace dyads with missing data, performance near floor on problem sets, prior close friendship, and extreme scores on the Math SAT and problem-solving comfort scales to attempt to minimize differences in average math skill/problem-solving comfort across the conditions.

The gender composition of the dyads was left free to vary in this experiment. The distribution of same gender dyads (male and female) and mixed gender dyads is shown in Table 2 for descriptive purposes. Gender composition did not affect the pattern of results from the training manipulation (gender composition × training composition interaction, *F* < 1.35).

**Design**

This experiment utilized a 3 (dyad training composition) × 2 (type of problem) mixed design. The first factor (dyad training composition) was manipulated between subjects and was referred to the kind of training the dyad members received; this factor had three levels. In the first level, both members of the dyad received the same procedurally based training. In the second level, both members received conceptually based training. Together, these two levels constitute homogeneous dyads. In the third level (diverse dyads), each of the dyad members received one of the two versions of the training, with one member receiving the procedural training and the other receiving the conceptual training. The second factor (type of problem) had two levels, which were manipulated within subjects, each one corresponding to different problem types (either standard or transfer). The first level (standard problems) included problems that were similar to the problems presented in the training sequences. The second level (transfer problems) consisted of problems that were either unanswerable or problems that required participants to extend beyond what they were explicitly taught during the training phase to answer the problem. A more complete description of the experimental problems is provided in the Materials section. All of the participants were presented with both of the problem types.

<table>
<thead>
<tr>
<th>Gender composition</th>
<th>Training condition</th>
<th>[Procedural]</th>
<th>Conceptual</th>
<th>Diverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female–female</td>
<td>7</td>
<td>7</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Male–female</td>
<td>5</td>
<td>11</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Male–male</td>
<td>8</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Group synergy and group common ground theory descriptions and predictions

<table>
<thead>
<tr>
<th>Theory</th>
<th>Key features</th>
<th>Predicted performance</th>
<th>Predicted communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common ground</td>
<td>Similar training/ background</td>
<td>Should be more successful in solving problems than cognitively diverse dyads, because of shared problem representations</td>
<td>Should spend a greater proportion of their communications on high-level discussion of solution planning and should have more positive impressions of their interactions than diverse dyads</td>
</tr>
<tr>
<td></td>
<td>More effective communication because of similarity</td>
<td></td>
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<tr>
<td></td>
<td>More easily constructed shared representations</td>
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<td></td>
<td>because of similarity</td>
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<tr>
<td>Group synergy</td>
<td>Diverse training/ background</td>
<td>Should be more successful in solving problems (particularly transfer problems) than cognitively homogeneous dyads because of discussion of multiple solution alternatives</td>
<td>Should spend a greater proportion of their communications on high-level discussion of solution planning because of discussion of multiple solution alternatives</td>
</tr>
<tr>
<td></td>
<td>Generation of more alternative problem solution plans/ representations</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Materials

Both paper-based and computer-based materials were used in this experiment. The paper-based materials included the arithmetic ability test, the working relationship questionnaire, and the background questionnaire. The computer-based materials consisted of two PowerPoint training lessons (a procedurally based training lesson and a conceptually based training lesson), the experimental problem set and the virtual workspace that was used for collaborative problem solving.1

Arithmetic ability test

Participants were asked to solve 10 problems requiring basic arithmetic operations such as addition, subtraction, multiplication, and division, as well as using fractions, exponents, order of operations, basic algebra, and basic probability. Two example problems from this test are ‘¼ × ½ = _’, and ‘(10 – 7) × 3 = _’.

Background questionnaire

The background questionnaire sampled participants’ background demographic information, previous math and statistics course experience, and their self-rated abilities and comfort in statistics and problem solving.

Working relationship questionnaire

This survey was intended to provide a subjective measure of the quality of the working relationship between dyad members. Participants were asked to indicate their level of agreement on the statements: ‘I worked well with my partner’, ‘My partner performed very well on the problems we worked on together’, ‘I would like to work with my partner again’, ‘How well do you know your partner?’, ‘My partner had a good understanding of the problems we worked on’, and ‘I made hardly any effort to explain the problem solutions to my partner’. Responses to these items were rated on a 1- to 5-point Likert scale. This assessment was given to each dyad member individually, and the total for all items was subtracted from 30 so that higher scores indicate more positive perceptions of the working relationship. The individual member scores were then combined, and a mean score was obtained. This mean score represented the working relationship score for that dyad.

Procedurally based training lesson

Both lessons were adapted from materials used by Mayer and Greeno (1972). In both lessons, individuals received instruction on how to apply the binomial formula, including the calculation of combinatorial probability, joint probability, and binomial probability. Participants received equivalent exposure to formulas, but the instruction about the formula was organized and presented in different ways. The same examples and practice problems were used in both versions of the training lessons.

The procedurally based lesson consisted of 21 slides organized in a computation-focused approach. Individuals viewed each slide on their own pace and were allowed to move forward or backward through the lesson slides. This lesson began by introducing the binomial formula: \( P(RN) = C(N, R) \times \binom{P,R}{N} \times (1 - P)^{N-R} \). It then simply asserted that there are three components of the formula \( C(N, R) \), \( P^R \), and \( (1 - P)^{N-R} \). In the second part of the lesson, the \( C(N, R) \) part of the formula was discussed. Participants were given the formula for finding \( C(N, R) \) and were shown how to compute the formula step by step. After completing this part of the lesson, the participants were given a practice problem to solve for \( C(N, R) \). The third part of the lesson followed the same format as the second lesson, but covered the \( P^R \) term. This lesson walked the participants through the step-by-step procedure of how to compute the \( P^R \) term and then ended with a practice problem on this term. The fourth part of the lesson covered the \( (1 - P)^{N-R} \) term. This lesson followed the same format as the previous two and ended with a practice problem on computing \( (1 - P)^{N-R} \).

Once the participants completed the four parts of the lesson, they were shown the step-by-step procedure for computing the whole formula and then shown a worked example in the context of rolling dice. On the last slide, the participants were given a final practice problem to compute binomial probability \( P(RN) \) given the values \( P=\frac{1}{4}, N=5, \) and \( R=2 \). Once the participants successfully answered this question, they were finished with the training phase of the experiment.

Conceptually based training lesson

The conceptually based lesson consisted of 26 PowerPoint slides. As in the procedurally based lessons, individuals viewed each slide at their own pace and were allowed to move forward or backward through the slides as needed. First, participants were given a general introduction to the concepts that are important for thinking about probability. The lesson introduced and defined in familiar terms the concepts of trials, outcomes, sequences, successes, probability of success, and the probability of failure. These concepts were illustrated using an example about rolling dice. The remainder of the conceptually based training followed a similar format to the procedurally based training in that the second part of the lesson covered the \( C(N, R) \) term. However, in the conceptually lesson, this component was discussed as a measure of ‘combinations’ or the number of ways that success can occur. The third part of the lesson covered the \( P^R \) term, but discussed it as a way to quantify the concept of the probability of a particular outcome. The fourth part of the lesson covered \( (1 - P)^{N-R} \) and discussed it as a way to quantify the concept of probability of failure. Finally, in the final part of the lesson, students were presented with the full formula for the first time. This section also included a worked example of computing \( P(RN) \). As with the procedurally based training, the same final practice problem was presented at the end of the lesson.

Virtual workspace

Dyads cooperatively solved the probability problems through the medium of a virtual chat. The virtual workspace display was split into two windows, one above the other. The top window contained a record of the dialog between a participant and

1 Electronic copies of all materials and a screenshot of the interface used in this study are available upon request. Please contact the first author at mattcanham@yahoo.com to obtain copies.

2 The notations used in these probability problems used the symbols \( C(N, R) \); however, this is one of a variety of common expressions. The reader is referred to http://www.mathsisfun.com/combinatorics/combinations-permutations.html for examples of other frequently used expressions.
their problem-solving partner. The message entry box was also contained in the upper window. The lower window displayed the problems that the dyads were to answer, two help buttons, an answer submission window, and an answer submission button. The two help buttons are linked to pop-up windows with either a list of the formulas or a list of the definitions, which were available to participants throughout problem solving.

Using this virtual environment as a medium for problem solving is not unlike texting, sending email, or using online chat facilities to contact a friend while doing homework from a posted PowerPoint presentation. This practice is not uncommon among US students today and is a basic feature in many computer supported collaborative learning or intelligent tutoring environments (Anderson, Corbett, Koedinger, & Pelletier, 1995; Rummel & Spada, 2005). Especially in distance education or peer tutoring settings, instructors often post PowerPoint lessons and have students interact with other students online as they engage in learning activities (using Blackboard or a similar facility). Further, there are certainly cases where students in more traditional settings fail to attend lectures and instead choose to learn through the posted course materials and interaction with peers as they complete homework assignments.

In addition, using the virtual workspace as a platform for collaborative problem solving offered several advantages for data collection. First, using automated performance measures and embedding them within the task environment reduces task disruptions (as opposed to pausing the experiment to obtain an assessment of mental representations or proficiency). Second, the online communications can be used as the group equivalent of using thinking aloud or verbal protocol techniques to assess the mental processes of individuals (Cooke, Salas, Kiekel, & Bell, 2004). Third, experimenter measurement errors were also reduced because the communications were recorded automatically.

**Experimental problem sets**
The dyads solved 18 problems, two of these were warm-up problems given at the beginning followed by 16 experimental problems. Of the experimental problems, half were standard problems and half were transfer problems. Following Mayer and Greeno (1972), standard problems consisted of items that required the same procedures as the practice problems that participants were given during the training lessons \((N=4, R=3, P=.2)\). What is \(P(R|N)\)? If a success is defined as rolling a 1 or 2 on a die, and a die is rolled five times, what is the probability that there will be successes on exactly two of the trials? Transfer problems required recognizing when new items were unsolvable \((R=4, N=5, P=R-N)\). What is \(P(R|N)\)? or answering questions about the formula \(C(N,R)\) be smaller than \(R\)? The order of the experimental problems was randomized.

**Procedure**
First, participants were randomly assigned to separate rooms as they entered the experimental area. The participants remained separated from each other throughout the experiment, were not able to communicate face-to-face, and were not informed about who they had been paired with. They could not see or hear each other throughout the experiment. After they entered their separate workspaces, informed consent was obtained.

Second, participants were given the arithmetic test without a time limit. This test was intended to ensure that participants had the requisite mathematical knowledge necessary to understand the training and perform the experimental task. All of the participants scored near ceiling.

Third, participants were given training on binomial probability. Depending upon their experimental condition, participants received either the same or different training programs as their dyad partner. If they were assigned to a condition in which the dyad members receive different types of training, then they were randomly assigned to either the procedurally based training lesson or the conceptually based training lesson. Participants were allowed to complete the training lessons at their own pace with no time limitations.

Fourth, participants began the problem-solving phase of the experiment. While solving the experimental problems, dyad members communicated through the virtual workspace. To familiarize participants with this environment, we gave them a brief tutorial on how to use the virtual workspace. Participants were also given two warm-up problems to make certain that both participants felt comfortable using the interface and to practice collaboratively solving problems with their partner. Participants were then presented with the experimental problems that they were instructed to solve collaboratively with their partner. To control for order effects, we randomly ordered the experimental problems. Once participants agreed upon a solution to a problem, both members entered their answers independently through their computer terminals. Participants’ answer submissions were monitored by the experimenter. If the dyad member’s answers did not match, the submission was rejected, and both participants were asked to re-enter their answers. A mismatch between participants’ answers only occurred a few times, and these were quickly corrected. When encountering unsolvable problems, the participants needed to agree that the problem was unsolvable and then indicate ‘unsolvable’ as their response.

Fifth, participants separately completed two questionnaires. The first questionnaire was the working relationship questionnaire. The second questionnaire was the background questionnaire. Once finished, the participants were debriefed, thanked, and excused.

**Chat Transcript Message Coding**
Each chat transcript was segmented into messages, with a message defined as all of the characters contained within a single chat submission—that is, everything that was typed before pressing the send button. Each message was coded into one of four categories: Off-task discussion—communications that were not directly relevant to solving the problem, such as ‘I’m hungry’ or ‘r u in psych 1?’ Solution development—interactive communications in which group members collaborate to plan a solution to a problem, such as indicated in the following exchange:

1. ‘what’s success defined as’
2. ‘\(R\) would be \(2(N-R)\)
3. ‘because success is evens coming up’
Message verification—communications consisting of statements to be verified, with no new solution information being added or negotiated, such as these exchanges:

1. “yes to both?”
2. “yes to both”
3. “I think unanswerable”
4. “I think so too”
5. “56?”
6. “yes”

Interface negotiation—communications that referred to orientation within the interface or statements about the readiness to receive a message, such as

1. “Hello, I am on Problem #4”
2. “OK”

Inter-rater reliability for a subset of 1137 randomly selected messages was kappa = .89. Disagreements were resolved by consensus.

RESULTS

We compared the dyads from the diverse and homogeneous conditions on five kinds of dependent measures: background characteristics, problem-solving accuracy (i.e. proportion correct on standard and transfer problems), problem-solving time (i.e. number of minutes required to solve standard and transfer problems), communication style (i.e. proportion of communications in each of four categories), and perceptions of the working relationship (i.e. score on a questionnaire concerned with perceived commonality with one’s problem-solving partner).

Did Conditions Differ on Basic Characteristics?

An important preliminary question concerns whether the individuals in each condition differed on basic characteristics in spite of random assignment. As shown in Table 3, the three conditions did not differ on any of the background measures including proportion correct on the arithmetic ability pretest, mean score on questionnaire items related to comfort with statistics and problem solving, mean high school GPA, mean reported Math SAT, and Verbal SAT scores. ANOVAs (with alpha set at .05) indicated that the conditions did not significantly differ on any of the basic characteristics we measured (all F’s < 1.01). Some data were missing for several self-report measures and ratings. Sample sizes as available for each analysis are indicated in the table.

Did the Conditions Differ on Problem-Solving Accuracy?

According to group synergy theory, the diverse dyads should perform more effectively than the homogeneous dyads; whereas according to common ground theory, the homogeneous dyads should perform more effectively than the diverse dyads. Table 4 shows the mean proportion correct on standard problems and transfer problems. A 3 × 2 repeated measures ANOVA revealed no main effect for condition on overall accuracy (F < 1), but there was a significant effect for problem type, in which standard problems were solved more accurately than transfer problems, F(1, 57) = 4.95, MSE = .02, p < .03, R² = .08. Importantly, there was a significant condition by problem type interaction, F(2, 57) = 4.72, MSE = .02, p < .01, R² = .14. Follow-up tests revealed that homogeneous dyads performed better on standard problems whereas the diverse dyads performed better on transfer problems, F(2, 58) = 8.78, MSE = .02, p < .01, R² = .13. When the goal is to solve standard problems—that is, problems such as those encountered during training—then homogeneous dyads were more effective; when the goal is to solve transfer problems—that is, problems that require a novel solution—then diverse dyads were more effective.

Did the Conditions Differ on Problem-Solving Time?

There were significant differences between the diverse and homogenous training conditions in problem-solving time F(1, 58) = 4.62, MSE = 213.3, p < .04, R² = .07. Overall, diverse dyads (M = 69.55, SD = 12.5) took longer than homogenous dyads (M = 60.95, SD = 15.5). However, follow-up least significant difference (LSD) tests (with p < .05) indicated that the shorter times were driven by dyads in the conceptual training condition (M = 55.3, SD = 16.0) who took less time to solve than dyads in the procedural training condition (M = 66.6, SD = 13.1), or the diverse training condition.

Did the Conditions Differ in Communication Style?

Table 5 shows the mean proportion of messages falling into each of the four coding categories (Off Task, Solution Development, Message Verification, and Interface Negotiation) across all problems for dyads in each condition. As can be seen, there was a significant effect of condition on solution development.

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Table 3. Demographic and background measures for each training condition

<table>
<thead>
<tr>
<th>Measure</th>
<th>Training condition</th>
<th>M</th>
<th>SD</th>
<th>M</th>
<th>SD</th>
<th>M</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Math pretest (N = 120)</td>
<td></td>
<td>0.88</td>
<td>0.12</td>
<td>0.87</td>
<td>0.15</td>
<td>0.90</td>
<td>0.10</td>
</tr>
<tr>
<td>Statistics comfort (N = 119)</td>
<td></td>
<td>29.3</td>
<td>5.86</td>
<td>28.1</td>
<td>8.25</td>
<td>30.3</td>
<td>6.68</td>
</tr>
<tr>
<td>Problem-solving comfort</td>
<td>(N = 118)</td>
<td>18.6</td>
<td>2.51</td>
<td>17.6</td>
<td>3.75</td>
<td>18.0</td>
<td>3.00</td>
</tr>
<tr>
<td>High school GPA (N = 118)</td>
<td></td>
<td>3.72</td>
<td>0.39</td>
<td>3.76</td>
<td>0.30</td>
<td>3.77</td>
<td>0.40</td>
</tr>
<tr>
<td>Math SAT (N = 95)</td>
<td></td>
<td>640.0</td>
<td>57.3</td>
<td>622.0</td>
<td>87.7</td>
<td>644.4</td>
<td>67.9</td>
</tr>
<tr>
<td>Verbal SAT (N = 92)</td>
<td></td>
<td>623.8</td>
<td>88.5</td>
<td>637.0</td>
<td>73.1</td>
<td>631.2</td>
<td>78.5</td>
</tr>
</tbody>
</table>

Table 4. Proportion correct for homogeneous and diverse dyads by problem type

<table>
<thead>
<tr>
<th>Training condition</th>
<th>Types of problem</th>
<th>M</th>
<th>SD</th>
<th>M</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneous</td>
<td></td>
<td>0.72</td>
<td>0.16</td>
<td>0.63</td>
<td>0.15</td>
</tr>
<tr>
<td>Procedural</td>
<td></td>
<td>0.75</td>
<td>0.16</td>
<td>0.63</td>
<td>0.15</td>
</tr>
<tr>
<td>Conceptual</td>
<td></td>
<td>0.70</td>
<td>0.17</td>
<td>0.63</td>
<td>0.15</td>
</tr>
<tr>
<td>Diverse</td>
<td></td>
<td>0.68</td>
<td>0.17</td>
<td>0.72</td>
<td>0.19</td>
</tr>
</tbody>
</table>
solving transfer problems. Thus, the answer to the question is: It depends. When the goal is to solve a routine set of problems efficiently, then cognitive diversity may be a detriment. When the goal is to be able to apply knowledge flexibly to novel problems, then cognitive diversity in problem-solving groups may be an asset.

Further, converging evidence was obtained by examining the communications between dyad members. The diverse dyads allocated a greater proportion of their messages to high-level discussion of solution planning. Thus, the data seem consistent with the conclusion that cognitive diversity prompts more discussion and elaboration of shared representations, which can impede routine performance, but at the same time promote the solution of non-routine problems in a more flexible manner. Meanwhile, the communication analyses suggested that students in homogenous dyads established shared representations more easily, which resulted in less discussion of solution-related processes. Although this efficient problem-solving behavior led to better performance on the routine problems, homogenous dyads were at a disadvantage on the transfer problems.

Finally, the homogenous dyads also showed more of a mutual enhancement effect and had more positive evaluations of their partner and their problem-solving effectiveness. However, these positive perceptions did not correlate with problem-solving accuracy on either standard or transfer problems.

As noted in the Introduction, previous studies on the effects of cognitive diversity on group performance have yielded mixed results (Horwitz & Horwitz, 2007, van Knippenberg & Schippers, 2007). The findings of this study suggest that there may not be an inherent asset or liability to being a cognitively diverse group, but rather that the potential benefits of diversity are, at least in part, moderated by the context of the situation, problem-solving task, or the goal to be accomplished. By examining both the properties of problem-solving dyads in terms of their prior training, and the properties of their interactions, we have shown that there are specific advantages of both homogeneous and heterogeneous dyads and each can be optimal for different kinds of performance. This interaction may partially account for some of the inconsistency in the literature (Harrison & Klein, 2007; Horwitz & Horwitz, 2007; Mannix & Neale, 2005; van Knippenberg & Schippers, 2007). It also supports theories of group cognition that have suggested that conflict may be an inherent consequence of diversity (Hinsz, et al 1997; Moreland & Levine, 1992), but also a critical one for innovation (Nemeth & Nemeth-Brown, 2003). Accordingly, Curseu, Schruier, and Boros (in press) have proposed that there are two dynamics underlying the effects of cognitive diversity in teams: a cognitive activation path that provides a larger knowledge base and a social rejection path in which divergent views expressed in group discussions lead to social rejection and relationship conflict. Conflict can be a double-edged sword that can both impede the construction of shared representations and at the same time can lead to superior group performance under some circumstances via the deeper processing required in order to resolve discrepancies.

From the perspective of the team diversity literature, the results of the present experiment demonstrate the value of conceiving of cognitive diversity as a construct distinct from other forms of diversity (Harrison & Klein, 2007; Williams &
O’Reilly, 1998). Further, the study broadens the research base by examining a new way of creating cognitive diversity through training that has direct implications for applied settings, including most obviously educational contexts and mathematics instruction. In this experiment, we defined cognitively diverse dyads as those in which the members were taught by different instructional methods, and cognitively homogeneous dyads as those in which both members were taught by the same instructional method. Importantly, although both forms of training were effective, neither type of homogenous dyad showed superior performance on the transfer problems. It was only when the two kinds of training were represented in the diverse dyads that the better transfer performance was seen.

The fact that improved transfer was only seen among diverse groups can be seen as evidence that the interaction of dyad members with different problem-solving approaches was critical for the development of a more complex understanding of the statistical content. One possible explanation for this result is that when different members have different perspectives, they can share those with each other, which gives the group access to multiple representations or multiple alternative solution paths. Access to multiple representations may then allow for more flexibility in future problem solving (Ainsworth, 2006; Kapur & Bielaczyc; in press; Wiedmann et al., in press). A more extreme suggestion is that through discussion, new, more complex representations emerge, which were not held by any member a priori (Curseu et al., in press; Schwartz, 1995).

Although in the present data we have no direct measures of representations or complexity that would confirm this account, determining this would be a very interesting direction for future work. What we did observe, however, is that the discrepancy in training among diverse dyads led to more high-level talk in relation to solution development, which led to more flexible problem-solving performance particularly on transfer problems. Thus, it seems plausible that either discussion of multiple solution paths or deeper, more complex processing of a shared representation may be mechanisms underlying the superior transfer performance of the diverse training dyads.

There are two main practical implications of this study for application in real-world groupsettings. First, the results suggest that a common training program might be used to create cognitively homogeneous groups when the goal is to create a positive working relationship among group members and to promote efficient solution of routine problems. Second, the results suggest that constructing workplaces of members to represent a variety of training approaches or prior experiences could be useful when the goal is to promote deeper collaboration between group members and higher levels of success of solving challenging non-routine problems. Although the results from the present study deal specifically with success in applying a particular statistical concept in a mathematical problem-solving context, it is an important question whether these results may generalize to other real-world settings including performance in small groups of learners on other educational content, as well as performance of teams in aviation or military settings, the business world, and or laboratories in science and medicine. The cognitive diversity examined in this study is somewhat related to the jigsaw method used to promote group learning (Aronson & Patnoe, 1997), in which different members of the team have different kinds of specific knowledge or are assigned specific roles in learning and problem-solving activities (Rummel & Spada, 2005). Additional research is needed to determine whether the same pattern of results would be obtained using a jigsaw approach.

A limitation of this study is that it was performed in a specific context with ad hoc dyads interacting through a virtual interface. There is an ongoing debate whether a dyad is really a group and whether dyads can offer the same affordances as other group sizes (Moreland, 2010; Williams, 2010). An interesting issue for future research is whether the pattern of results shown here will be specific to dyads or if it will obtain with group sizes of three or more. A further question is whether the virtual interaction affected the group performance and whether face-to-face interaction would yield different results. A final question that seems ripe for future research is whether the same pattern would be obtained after members of problem-solving groups have had extensive experience in working with each other. This is clearly an important direction for understanding which training approaches might be optimal in real-world situations where problem-solving teams or workgroups are established on a more permanent basis.

REFERENCES


M. S. Canham et al.


Williams, K. D. (2010). Dyads can be groups (and often are). Small Group Research, 41, 268–274.
