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Distributed Metacognition during Peer Collaboration

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Abstract

Current educational reform efforts stress the need for educators to teach critical thinking skills and use group-based pedagogical methods. However, the empirical literature is still unclear under which circumstances they are best fostered. The present study examined scientific reasoning as participants worked on a causal reasoning task alone versus with a partner. In previous work, individual working alone readily acquire new strategies and add them to their existing repertoire but do not abandon their less-effective strategies. The challenge of cognitive development lies not in the construction of new strategies, but rather in the consolidation of metastrategic knowledge that allows individuals to effectively evaluate and select strategies from their repertoire. The results of this research suggest that special emphasis should be placed in peer collaboration's role in fostering metastrategic understanding rather than focusing only on the development of strategies. Further, it suggests a benefit of collaboration not previously explored; the mutual reinforcement of each other's unstable metastrategic control through a process of distributed metacognition. Instead of deep collaboration about simple thought (theories and strategies), the benefits of collaboration for these participants lie in simple collaboration about deep thought (metastrategic knowledge).

Introduction

The last decade has seen a new emphasis on systemic educational reform in a variety of subject areas. Although each framework approaches reform from a different content perspective, they all emphasize that educators should use pedagogical methods that encourage collaborative work among students. Although the reform frameworks that have been developed do not offer any specific strategies for achieving these goals, a growing body of research suggests directions for reform.

The present study investigated the effect of peer collaboration on the development of scientific reasoning, looking particularly at the differences in strategy use when participants work alone versus when they work with a partner. The task materials, procedure, data coding, and analysis method are based on our previous studies of the development of science reasoning in individuals (Kuhn, Schauble, Garcia-Mila, & Andersen, 1992; Kuhn, Garcia-Mila, Zohar, & Andersen, 1995). In the present study, participants worked on two isomorphic scientific reasoning problems, one problem alone and the other with a partner. By using a within-subjects design, the differences in development of inferential reasoning strategies and metastrategic knowledge between the single versus paired condition could be viewed directly. The use of microgenetic

methodology allowed for a fine-grained examination of peer interactions and direct observation of the process of development. It was hypothesized that the analysis of the nature of peer interactions would find collaborative processes that distribute cognition in a manner that benefits participants' weak metacognition.

Conceptual Framework

The research literature suggests that a spectrum of benefits may co-exist within the collaboration of a single group. A relatively low level of benefit is accrued from simple exposure to other's strategies (e.g., Zimmerman & Blom, 1983). More benefit is gained when peers operate on one another's thinking (e.g., Berkowitz & Gibbs, 1983). At the highest level lies scaffolding (Wood, Bruner, & Ross, 1976), where a more-able partner structures and simplifies the learning environment to foster a less-able partner.

The benefits outlined in the literature emphasize the construction of new concepts and strategies. However, in the case of strategies, previous work with individual participants (e.g., Kuhn & Phelps, 1982) has shown that participants readily acquire new strategies of scientific reasoning and add them to their existing repertoire without abandoning their less-effective strategies. The challenge of cognitive development in this area lies not in the construction of new strategies, but rather in the consolidation of metastrategic knowledge (Kuhn et al., 1995) that allows individuals to effectively evaluate and select strategies from their repertoire. The present study compares not only the effect of peer collaboration on the construction of new reasoning strategies but also the role of metastrategy in peer collaboration.

Method

Many early studies of peer interaction relied on differences in pre- and post-test measures sandwiched around a period of treatment in an individual or group situation (Azmitia & Perlmutter, 1989). As empirical attention has focused on the quality of interaction, some researchers have looked at participants' behavior during the course of the treatment or even accelerated the course of development using microgenetic methodologies (Siegler & Crowley, 1991). However, when these fine-grained measurements have been analyzed, they generally have been collapsed into a single average across sessions instead of being analyzed as repeated measures (e.g., Dimant & Bearison, 1991). The present study takes full advantage of microgenetic measurement by looking not only at pre/post differences in

reasoning but also examining the effect of peer collaboration on the course of development.

Two reasoning tasks involving multivariable causal inference were used, one involving the determination of which features affect the speed of a computerized car, the other involving determining which features affect the speed of a model boat. These tasks were designed to be isomorphic with respect to number and levels of variables, number of outcomes, and the pattern of effects (or non-effects) of variables on outcomes and previous research has shown them to be comparable in difficulty level (see Kuhn et al., 1995, for a detailed description of the tasks and an analysis of task comparability).

Participants were 12 pairs of fifth-grade students from an elementary school in a lower-income urban area of a large U.S. city. The self-reported ethnic background consisted of 12 Hispanics, 8 African Americans, and 4 non-Hispanic Whites. There were 14 females and 10 males. All reported English as their first language, though 10 participants spoke some Spanish at home. Participants' mean age was 10 years, 6 months (range: 9 years, 10 month to 11 years, 5 months).

Participants worked weekly with one task alone and the other (counterbalanced) with a same-sex partner over the course of seven weeks. Sessions was audiotaped and transcribed later for coding.

Results & Discussion

Previous studies with these tasks show that participants possess a range of coexisting strategies (Kuhn et al., 1995). Analysis of strategy use in the present study indicates that collaboration did not benefit all strategies equally. For many of the strategies, participants possessed some degree of competence at the start of the study. For the number of features they intend to explore in a given experiment, the number of inferences they draw from experiments, and the number of experimental results they invoke as evidence to support an inference, participants performed at a moderate level and improved with practice during the course of the study. This suggests that for these strategies, participants were not discovering new strategies but were rather consolidating already existing strategies. There appears to be little difference between singles and pairs in the rate of improvement of these established strategies.

Use of Valid Inference

In contrast to the aforementioned strategies, valid inference (i.e., using controlled comparisons to justify causal and noncausal inferences) is a strategy that is only beginning to be used by participants at this age group. Figure 1 shows a pattern of development for this emerging strategy that is different than the pattern found for consolidated strategies. In the initial segment,¹ the use of

valid inference by singles and pairs was virtually zero ($M = .030$, $SD = .083$, and $M = .014$, $SD = .028$, for singles and pairs, respectively) and they improved in tandem in the middle segment ($M = .150$, $SD = .209$, $M = .153$, $SD = .236$). However, in the final segment, the pairs ($M = .438$, $SD = .368$) improved markedly over the singles ($M = .286$, $SD = .338$). Repeated-measures ANOVA found a significant effect for time period, $F(2, 46) = 23.77$, $p < .001$, and no main effect for social condition, but a significant interaction between social condition and time, $F(2, 46) = 6.82$, $p < .01$. The higher performance by the pairs in the final segment compared to the singles suggests that for emerging strategies, collaborating with a peer yields higher cognitive benefits than working alone (see Kuhn et al., 1995, for the criteria for coding inferences as valid and invalid).

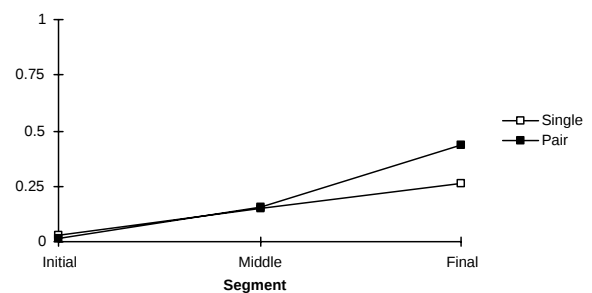


Figure 1: Proportion of valid inferences over total inferences.

Valid Inference Use in Individual Dyads Though the results across pairs indicate that the pairs had greater strategy gains than singles, an examination of each pair separately shows a range of performance. The 12 pairs fell into three patterns:

- (1) dyads in which the pair made greater strategic gains than either member alone (as measured by proportion of valid inferences drawn in the final segment) ($P > S$);
- (2) dyads in which one member of the pair made strategic gains while the other made little or no gain. The performance of the pair fell between the level of the two singles, reflecting a middle ground between the more-able and less-able partners ($S1 > P > S2$);
- (3) dyads in which little or no progress was made in the pair or single condition ($NP/P=S$).

The Emergence and Consolidation of Valid Inference In addition to their pattern of valid inference use, the three groups were also distinguished by the extent to which they explicitly intended to draw the valid inferences when they constructed their instances. In the $P > S$ and $S1 > P > S2$ dyads, valid inference of a feature tended to be preceded by a corresponding intent to find out about that feature specifically and an intent to experimentally isolate the variable.

Once the dyad began using valid inference, the strategy was often used in subsequent instances. However, when

¹ For each single and pair, the total number of experiments carried out within each task over the seven weeks (median = 33, range 31-34, $SD = .610$) was divided by 3; each third constituted a segment. Thus, a 2×3 (social condition $\times$ time) repeated measures Analysis of Variance (ANOVA) was performed, with social condition

(single, pair) as a within-subjects variable and time (initial, middle, final segment) as a repeated measure.

NP/P=S dyads drew valid inferences, it appears that it was only coincidence that the variable was controlled. When the instance was constructed, dyads rarely intended to specifically investigate the feature and there was no explicit plan to isolate the variable. In immediately proceeding instances, the strategy was not used again.

For instance, Pair J (a NP/P=S dyad) had their first valid inference as a pair in Session 4. In Instance 4.4 (the fourth instance in Session 4), J1 constructed a car with no apparent plan to isolate muffler; in fact, Pair J did not speak at all during car construction. J1 placed markers to indicate that they intended to find out about all five of the features by running this car. When she drew the inference, there was no indication that she realized that the nonfocal variables had been controlled:

J2: The first time it still went to number four and we used the muffler. This time it still went to number four and we didn't use the muffler.

After this valid inference, Pair J did not draw another valid inference until Session 6.

Valid Inference Use in P>S Dyads In contrast to Pair J, when Pair A (a P>S dyad) drew their first valid inference, it was in the context of an explicit plan to design a controlled comparison. As they chose the features for their boat in Instance 4.1, A1 proposed that they test the features one at a time:

A1: [Constructing new instance] Let's do it one by one. That's how we figure out how they matter.

A1 has stated a simple form of Tschirgi's (1980) "vary one thing at a time" (VOTAT) strategy to isolate variables.² A1 placed a marker to signify that they intend to find out about the boat size only. In constructing their boat, Pair A explicitly indicated a single feature to investigate and the intent to isolate the feature.

Participants commonly view a correct prediction of the boat's stopping point as proof of the correctness of their causal and noncausal beliefs. After they ran the boat in Instance 4.1 and it stopped at zone two as predicted, A2 was ready to draw an inference about the weight (a favorite feature of investigation for A2 in previous sessions), but A1 drew her back to the originally intended feature:

Experimenter: [After running boat] What did you find out?

A2: We [found] out about the weight.

A1: No, about the boat size, that's all.

A2: Oh, the boat size.

A1: Just talk about the boat size.

A1's feedback in response to A2's digression to the effect of weight kept them heading down the path toward drawing a valid inference on boat size later in Instance 4.2. They went on to draw a false inference about the effect of boat size, but

A1 quickly added that they intend to run a comparison boat and change only the boat size:

A1: Doesn't matter. The [boat size] doesn't matter. And we're going to try it again.

A2: Doesn't matter.

A1: We're going to change the boat size to [a large] boat.

In the next instance (4.2), A1 again took the lead in constructing the controlled comparison, though A2 was clearly in agreement in the use of the strategy:

A1: [Constructing new instance] Just change the small size.

A2: Change it to the small size.

Experimenter: OK.

A2: And that's all. And then that way we'll know for sure.

Experimenter: What features are you going to find out by running this boat?

A2: The boat [places marker on boat size].

Though A1 only began isolating variables in the previous instance, A2 already recognized its validity to test for certain if the size of the boat in causal or not. Her immediate adoption of A1's new strategy suggests some readiness for A2 to have constructed the strategy on her own.

They predict that the boat will stop at zone 2, but it actually stops at zone 4. Though participants in previous work with these tasks (e.g., Kuhn et al., 1992, 1995) had a tendency to revert to invalid evidence-based or theory-based justifications when faced with an unexpected outcome, Pair A accepted the disconfirmation of their belief and drew a valid inference of causality:

Experimenter: [After running boat] How do you know that the boat size matters?

A2: Because, um, we did it...

A1: We did the, we did the, we tried it boat, we tried it with the different size and there's one with everything but the size [i.e., same features except for size: Instance 4.1] and we changed it, so this one goes faster than this one.

A2: So the small ones go faster than the big ones.

The strategies used by Pair A in their Session 4 instances contrast with those used in their instances in the preceding session. In Instance 3.1, A1 stated that "We already know everything," convinced that they understood the complete causal structure of the task. However, they decided to test the features again in order remain out of their regular classroom for a period. A2 took the lead in designing which boats to run and in making predictions in how far the boats would travel. In Instance 3.2, it was A2 who suggested that they investigate one feature at a time (VOTAT):

A2: Why don't we just stick to one subject? Then we'll be like there quicker and without the card get all of them.

A2 constructed the instance, varying only boat size from the previous instance (4.1). However, A1 wanted to vary two features with the instance:

A1: I want to do this (boat size) and this (weight).

A1 became increasingly uncooperative with A2, with the

² Though isolation of variables and valid inference both involve controlled comparison, they differ in that isolation of variables is a strategy of investigation design (used when boats and cars are being constructed) while valid inference is a strategy of data analysis (generally used after a car or boat is run).

two reduced to name-calling by the end of the session.

In Session 4, Pair A had a new sense that they don't know the causal nature of the features and a renewed sense of purpose. A2's use of VOTAT in Session 3 and A1's isolation of variables at the start of Session 4 suggest that they were at a similar point of readiness to start controlling variables, though they appeared to have constructed the strategies individually. There was little explicit talk of the strategies as would be expected if scaffolding or joint construction were being employed and neither ever justified the use of the isolation of variables or valid inference strategies. Though A2 tried to use another, less-effective strategy at one point, A1's feedback returned them to their previous course. They went on to isolate variables and draw valid inferences consistently for the remaining three sessions, suggesting that their use of valid inference consolidated very quickly.

When Pair D (another P>S dyad) drew their first valid inference as a pair, they also showed an intent to isolate variables. By the third session as a pair, D1 and D2 had not draw any valid inferences while working together, though D1 drew a single valid inference in the single condition (Instance 2.3). In Instance 3.2, they drew a pair of false inferences, but included in their inference justifications were hypothetical propositions to isolate variables (e.g., "If we would put the smaller boat with the weight with the small sail, it will go I think to the black line, but if we would do the same [configuration of features], only with the bigger boat, I think it would go to the green"). The discussion following each proposal was minimal (simple agreements with no justifications), suggesting that the strategy may have already been present in their minds though they had not yet used it while together. The strategy did not emerge in response to any apparent sociocognitive conflict nor was there any co-construction beyond a simple statement of the intent to isolate a variable.

In the next instance (4.3), D1 began to draw an invalid inference about the effect of boat size, comparing the boat they ran (Instance 4.3: small boat, small red sail, no weight, deep water) to a previous boat that varied on weight but not size. D2 interrupted with a valid comparison with a boat two instances earlier (Instance 4.1, which varied from Instance 4.3 on boat size only):

Experimenter: Tell me about how you figured that out.

D1: In the smaller boat we put the weight...

D2: Our first boat, we put a smaller boat with no weight and the features were the same [Instance 4.1] and this one we put a bigger boat with no weight and the features were still the same, but it went slower, it went to the green and our first boat went to the red.

This interruption by D2 is reminiscent of the earlier example when A1 pulled A2's attention back to the feature that they had isolated. Though both A1 and A2 demonstrated an understanding of strategies such as valid inference and isolation of variables, these strategic digressions show the initial weakness of their metastrategic control over the new strategies.

How might these strategic digressions be conceptualized? Our previous work with individual participants (Kuhn et al., 1992, 1995) has shown that an individual's use of valid inference is swayed by idiosyncratic biases in exploration caused by their theories concerning the structure of the causal system (confirmation vs. disconfirmation, causal vs. noncausal), the affective investment in one's own belief, and social factors in the learning environment. The partner in the pair condition provides a check for regressions to false inference strategies due to unstable metastrategic control. The partner's feedback becomes an external version of the internal metacognitive argument that occurs when a strategy is selected for from an individual's repertoire. The intercession of the partners helped support an individual's faltering metastrategic debate; if A2 (for instance) had been working alone, she likely would have drawn an invalid inference. This metastrategic reinforcement provided by a partner may account for the improved performance of the pair condition over the single by these two dyads compared to the other participants.

The other two P>S dyads (B and C) had much smaller differences between the pair and single use of valid inference than did Pairs A and D. Their use of valid inference had some similarities but there were also notable differences.

Though Pair B had their first valid inference in Session 2, their use of valid inference resembled the NP/P=S pairs like Pair J for much of the study. They never expressed an explicit plan to isolate a variable and they did not begin coordinating a single intent to investigate with a subsequent valid inference until the end of Session 5. They began consistent use of valid inference (coordinated with a single intent) in Session 6. They gave no feedback that would suggest metastrategic support of one another's efforts.

Pair C did not show as rapid a rise in the use of valid inference as Pair B, but their reasoning showed characteristics that suggested that their use of valid inference was not as serendipitous as that of the NP/P=S dyads. When Pair C drew their first valid inference (Instance 6.2), it was coordinated with a single intent, though there was no explicit plan made to isolate the variable. Their subsequent use of valid inference was haphazard, with two additional valid inferences out of 11 total inferences. As with Pair B (who also showed erratic use of valid inference after its first appearance), there were no statements between them that suggest metastrategic support.

Valid Inference Use in S1>P>S2 In the S1>P>S2 dyads, the performance of the pair was intermediate between each partner's performance alone. For each of these dyads, one participant drew all of the inferences for the pair in three of the four pairs. In two of the four pairs (F and H), the partner who drew more inferences (i.e., socially-dominant) was also the partner with superior performance in the single condition, suggesting that for these two pairs, the performance of the pair can be accounted for exclusively by

the inferences drawn by the more-able partner. However, for the other two pairs (E and G), it was the less-able partner when single who drew the majority of valid inferences for the pair, suggesting that in these pairs, the performance of the pair is due to benefits of collaboration to the less-able partner.

In Instance 4.2, H1 took the lead and constructed an uncontrolled comparison of wheel size. When they drew an inference about the effect of wheel size (a three-level variable), they both noted that a third instance was needed:

Experimenter: [After running car] So which wheels go fastest?

Both: Medium.

H1: I don't know yet.

H2: We got to try, but I think it's the medium.

H1: If we try the next car, then we'll know between the other two.

In the next instance (4.3), H1 tried to isolate wheel size. However, H2 wanted to vary multiple features:

H1: [Constructing new instance] The same thing except for the wheels. Change the wheels whatever way you want.

H2: Why can't it be a big engine?

H1: No, because you're going to find out the wheels.

H2: The color white.

H1: No, alright?

Through the rest of Session 4 and through Session 5, H1 continued to isolate one variable at a time, while H2 consistently objected in vain to H1's attempts. H1 tried to explain the strategy to H2 on numerous occasions. Here, they have run one car (5.4) with a fin to find out the effect of fin. H2 was satisfied that the single instance demonstrated the causal nature of the fin and she wanted to change the muffler in Instance 5.5 to investigate its causal nature:

H1: [Constructing new instance] Same exact car except we want to change it to no fin. That one [5.4] went to four, right?

H2: We have to go to the muffler.

H1: Let's try three.

H2: We have to go to the muffler now.

H1: No, we need to...we're still fin now.

H2: I know...oh, we are?

H1: Yeah, because you got to run it with and without the fin. Then after this one, we get a chance to find out about the muffler, not today but next time.

In Session 6, H2 stopped actively resisting H1's efforts to isolate one feature at a time and instead looked to H1 to lead their investigation:

Experimenter: What type of car would you like to look at first?

H2: [To H1] Small? Big? Hello? Come on, let's go. Small? Hello? Wake up in there, wake up in there.

Experimenter: [After running car] What did you find out?

H2: [To H1] Come on, let's go on. What did you find out?

By the end of Session 6, H2 accepted H1's isolation of variables strategy, though H2 still was following the lead of H1:

H1: [Constructing the car] Everything the same again.

H2: Everything the same.

Throughout the remaining sessions, H1 initiated nearly all the car designs, intents, and inferences. Though H2 accepted H1's use of controlled comparison, H2's lapses in its use suggest a lack of understanding of the strategy. Here, H1 plans to test the effect of the fin, while H2 wants to change the wheels:

H1: [Constructing car] OK--now we going to find out about the muffler and leave that like that....Nononono, that made it to 3, so let's try it like this. The muffler don't matter. The fin, got to try the fin.

H2: Why don't you change the wheel?

H1: We're going to three, yeah, because the engine is big so it's going to help the car go faster.

H2: Change the wheels.

H1: And the medium wheels are going to help, too, because the big wheels and the little wheels go the same speed, and that's it.

H2: Change the wheels.

H1: Nope, no, I say no no. It's too late.

And in H1's later attempt to test the effect of the muffler, H2 again wants to change the wheels as well:

H1: [Constructing car] I'll have the same car except I want to leave off the muffler.

H2: Why won't you change the wheel?

H1: 'Cause we're going to find out about the muffler.

Though H2's resistance to H1's strategies diminishes with time, H2 never used isolation of variables or valid inference herself (H1 drew all 12 valid inferences for the pair). Her constant desire to design uncontrolled comparison suggests that she hasn't constructed the isolation of variables or valid inference strategy yet. Unlike A1 and A2 and the other P>S dyads, in which both partners understand the need to isolate variables and seem to reinforce each other's efforts, only H1 seems to understand the strategies being employed. Rather than collaborating together, H1 is pulling the less-able H2 along.

H1's social and intellectual dominance of the pair's interactions suggests that in the S1>P>S2 dyads, the more-able partner dominated the pair and that the valid inference performance of the pair was due solely to the efforts of the more-able partner. However, in two of the four dyads, it is the less-able partner who draws more valid inferences for the pair. In these two dyads (E and G), the less-able partner (E1 and G2, respectively) benefited from the collaboration, performing with their partner at a higher level than when working alone.

For example, G1's performance as a single was much higher than G2's, yet when they were paired, G2 drew more valid inferences than G1 (four vs. three inferences). In Instance 6.5 (one session after the pair's first valid inference), G1 and G2 worked together to change the car from the previous instance to construct a controlled test of

engine size. After changing the size of the engine from large to small, G2 tried to change another feature as well, but G1 brought her back to isolating one variable:

G2: Move this.

G1: No, you got to leave it the same, all these.

G2: OK.

They continued to construct the boat, and once again, G2 tries to vary another feature:

G2: Wait--big muffler.

G1: No, it's the same. Leave it the same.

G2: OK.

Had G2 been working alone, it appears she would have gone on to draw an invalid inference using an uncontrolled comparison. Through G1's intervention, G2 returned to isolating engine size and went on to draw a valid inference.

Though G1 and G2's interactions suggest that metastrategic reinforcement may play a role in fostering the performance of the less-able partner, the verbal interaction between E1 and E2 has little evidence supporting such a hypothesis. Instead, the dyad appears to have divided the subtasks between them. Beginning with their first valid inference in Instance 7.1, the more-able E2 constructed all of the inferences, chose the features they tended to pursue, and placed the markers to indicate which features they found out about. The less-able E1 drew the inferences. As a result, E2 was performing the problematic processes of intending to isolate the feature in question and coordinating the intent to find out about a feature with the inference subsequently drawn, strategies that are missing in the haphazard valid inferences drawn by the NP/P=S group.

Though E2's actions appeared to simplify the task to allow E1 to draw a higher proportion of valid inferences than he would otherwise working alone, there is no evidence that E2 intentionally simplified the task for E1's benefit. Therefore, E2's simplifications were not consistent with the present study's conception of scaffolding, which requires the more-able partner to intentionally structure a task so as to reduce its complexity or difficulty.

In all four of the S1>P>S2 dyads, one partner dominates the pair when drawing inferences, though that does not translate into intellectual dominance. In the cases of Pair F and Pair H, the valid inference performance of the pair is due exclusively to the more-able partner, whose use of isolation of variables and valid inference strategies is sometimes at direct odds with the intentions of the less-able partner. However, in the cases of Pair E and Pair G, the less-able partner (E1 and G2, respectively) drew most of the valid inferences and appeared to benefit from the presence of the more-able partner.

In the present study, collaboration did not benefit all reasoning strategies equally. For example, no significant differences were found between the single and paired condition for strategies that were familiar and often used, nor were there differences in the emergence of new strategies. Instead, the advantage of collaboration over working alone was seen during the period immediately after the appearance of a new strategy (in this case, the use of

controlled comparisons to draw valid causal inferences), when the use of the strategy was being consolidated.

The case studies presented here suggest that the benefit of collaboration for the participants in this study appears to be in the distributed support of unstable metastrategic knowledge rather than the construction of strategic knowledge, as has been suggested by the research literature. By providing a check for regressions to false inference strategies due to unstable control of metastrategic knowledge, the partner's feedback becomes an external version of the internal metacognitive argument that occurs when a strategy is selected for from an individual's repertoire. The intercession of the partners helped support an individual's faltering metastrategic debate. This metastrategic reinforcement serves as a form of distributed metacognition and appears to account for the improved performance of the pair condition over the single in this study.

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