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# Explanation and Generalization in Young Children's Strategy Learning

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Children often learn new problem-solving strategies by observing examples of other people's problem-solving. When children learn a new strategy through observation and also explain the new strategy to themselves, they generalize the strategy more widely than children who learn a new strategy but do not explain. We tested three hypothesized mechanisms through which explanations might facilitate strategy generalization: more accurate recall of the new strategy's procedures; increased selection of the new strategy over competing strategies; or more effective management of the new strategy's goal structure. Findings supported the third mechanism: Explanations facilitated generalization through the creation of novel goal structures that enabled children to persist in use of the new strategy despite potential interference from competing strategies. The facilitative effect of explanation did vary with children's age and did not vary between explanations children created by themselves versus explanations they learned from the experimenter.

## INTRODUCTION

Children often have the opportunity to learn new strategies by observing the problem-solving of the people around them. However, when children learn a new strategy through observation, they often must do so without the other people explaining the logic of the strategy. Of course, children could simply memorize the observable actions of a strategy and later try to reproduce them by rote. In contexts where performing similar actions in a constant order yields successful performance, this can be sufficient to learn new skills. But in many domains, successful solutions must be tailored to the specifics of each situation. Without understanding why a strategy works, children may be unable to generalize the new strategy across even minor variation in the problem-solving context.

Thus, children often need to answer several questions about problem-solving procedures that they observe. What subgoal was each procedure designed to meet? Why did the problem solver choose one procedure over another? Which procedures were essential to the success of the solution, and which might be varied without rendering the strategy ineffective? Across a range of ages (5-year-olds, 13-year-olds, college students), a variety of tasks (physics, computer programming, biology, and number conservation), and a variety of types of to-be-explained material (example problems, textbook passages, and oral judgments of adults), the extent to which problem solvers explain what they see has been found to be closely related to success at generalizing strategies learned from examples (Bielaczyc, Pirolli, & Brown, 1995; Chi, Bassok, Lewis, Reiman, & Glaser, 1989; Chi, de Leeuw, Chiu, & LaVancher, 1994; Siegler, 1995).

Three factors have been associated with the facilitative effect of explanation on generalization. First, the sheer quantity of explanation is important. Learners who generate more explanations generalize new strategies more widely than those who generate fewer explanations (Chi et al., 1989, Chi et al., 1994). Second, the content of explanations is important. Explanations facilitate generalization most when they refine or expand the conditions of action, identify additional consequences of an action, or impose a goal or purpose on an action (Chi et al., 1989; Chi et al., 1994). Third, the object of explanation is important. When children focus on explaining the advanced problem-solving strategies of an adult, they learn new strategies more effectively than if they focus on explaining their own less-advanced strategies (Siegler, 1995).

Although these findings provide information about the kinds of explanation that facilitate generalization of new strategies, little is known about exactly how that facilitation occurs. In the present study, we tested three hypotheses about the mechanisms through which explanation facilitates generalization of observed strategies: (1) explanations make it easier to recall procedures within the strategy, (2) explanations favor selection of the strategy over established alternatives, and (3) explanations make it easier to keep track of subgoal execution within the strategy. We next consider the basis for each of these hypotheses.

With regard to the first hypothesis, explanations may provide an elaborative context that makes it easier to recall the original example. Transfer requires recall of the strategy being transferred. Using a strategy once or a few times may be insufficient for recalling it later. However, if children generate explanations as they learn the strategy, the explanations may strengthen

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access routes to it and provide multiple cues for recalling it. In other words, explanations may enhance recall via the well-established depth of processing principle (e.g., Bobrow & Bower, 1969; Jacoby, 1978; Slamecka & Graf, 1978).

With regard to the second hypothesis, explanations may promote generalization of new strategies by favoring their selection over that of older, better-established competitors. Children often fail to immediately generalize new strategies to all applicable contexts. Sometimes, they fail to use the new strategy altogether; other times, they use the new strategy occasionally, but also continue to use older, less effective approaches (Kuhn, Garcia-Mila, Zohar, & Andersen, 1995; Schauble, 1990, 1996). Explanations may assist in generalization of example strategies by specifying the optimal selection criteria. In metacognitive theories of strategy choice, this specification would occur through creation of explicit declarative knowledge about desirable properties of the new strategy (Fabricius & Hagen, 1984). In associative theories of strategy choice, this might entail the creation of "novelty points," which temporarily boost the strength of a new strategy relative to the strengths of existing strategies (Siegler, 1996). Regardless of the particular mechanism used, the outcome would be the same: Generating explanations for the superiority of a new strategy would increase its likelihood of being selected.

With regard to the third hypothesis, explaining the logic underlying a strategy may help children keep track of their current location within a strategy's subgoal stack. Successful execution of a strategy typically involves satisfying a sequence of subgoals. Even on simple problems, the cognitive resources necessary to plan out the execution of a strategy can exceed children's limits (Klahr, 1985; Klahr & Robinson, 1981). Resource constraints may be an especially critical obstacle in situations where successful execution of a strategy depends on the actions of another individual (Crowley & Siegler, 1993). For example, in game-playing situations, children often must balance offensive and defensive goals. If a child initiates an offensive gambit that takes several turns to evolve, she must keep herself from being sidetracked as she executes each necessary subgoal in the strategy. Explanations may provide a framework linking the subgoals within a strategy and thus making it easier for children to assess what they have already done and what they must do next to continue successful execution.

In addition to exploring the contributions of these three mechanisms to the facilitation of generalization, the current study provides two extensions of prior work on children's explanation. First, the study provided a direct developmental comparison of the efficacy of explanations in promoting generalization. Young children often lose track of their overall goal when they are distracted by the immediate situation (Vygotsky, 1962). This may make keeping track of subgoals within the new strategy especially important in their successful use of it. Prior studies of self-explanation have demonstrated that explanations facilitate the strategy generalization of kindergartners (Siegler, 1995), eighth graders (Chi et al., 1994), and undergraduates (Bielaczyc, Pirolli, & Brown, 1995; Chi et al., 1989). However, because these studies did not include children of different ages working on the same problem, they do not provide direct information as to possible developmental differences. The current experiment enables direct comparisons of the roles of explanation in promoting kindergartners', first graders', and second graders' generalization.

Second, the current study extends prior work by including at least two kinds of explanatory contexts. Whereas prior work has focused on children's self-generated explanations, this is only one path through which children learn explanations of problem-solving examples. In everyday settings children often participate in joint problem-solving activity with their parents, and parents sometimes engage the children in explanatory conversations about the problem-solving activity (e.g., Callanan & Oakes, 1992; Crowley & Callanan, 1998; Korpan, Bisanz, Bisanz, Boeheme, & Lynch, 1997). This study tested whether the facilitative effect of explanations depends on whether the explanations are true self-explanations (i.e., generated by the child without help from an adult) or are learned by hearing an adult offer their own explanation for the example.

## Tic-Tac-Toe as an Explanation Problem

The task chosen to investigate children's explanations was tic-tac-toe. In this game two players take turns drawing Xs and Os on a $3 \times 3$ grid. Winning involves a player placing three Xs or three Os in a row, column, or diagonal. Tic-tac-toe is especially suited to a study of explanation-based learning because learning from examples is probably one of the primary paths through which children actually learn about the game. As a two-person competition, tic-tac-toe is an inherently social enterprise. Whether children's opponents are other children, adults, or computer programs, each game represents an opportunity to learn from observing another player's approach. Furthermore, most opponents are likely to want to confuse and defeat their competitors rather than to talk about the logic behind their strategies. Thus, the extent to which children learn from the tic-tac-toe strategies of others is likely to depend in large part on the extent to which they can construct explanations that accurately account for the sequences of moves they observe.

In earlier work, a developmental progression of tic-tac-toe strategies was identified (Crowley & Siegler, 1993). The large majority of kindergartners, first graders, and second graders, as well as about half of third graders, use the *win/block* strategy. They first attempt to find a move that will win the game. If a winning move is not possible, they look to see if they can make a blocking move so that their opponent does not win. If they can neither win nor block, they attempt to put a second X in a row, column, or diagonal so that—if their opponent fails to block—they can win on their next turn.

By third grade, many children begin to use the more sophisticated *fork* strategy. This approach involves trying to create a configuration with two separate winning paths. Even if the opponent blocks one, the player can win by completing the other. As the game proceeds, a player using the fork strategy first looks for squares where a win is possible, then for squares where a block is needed, and then for possible forks. The fork strategy represents a leap in tic-tac-toe savvy. Rather than relying on the opponent's mistakes to create opportunities to win, players using the fork strategy try, from the beginning of the game, to create a situation where they can win no matter what their opponents do.

Because many children from kindergarten to second-grade use the same strategy, tic-tac-toe provides a convenient environment for studying developmental differences in self-explanations. In many domains, older children use qualitatively different strategies than younger ones, making it difficult to determine whether differences in learning are due to differences in domain-specific knowledge or in domain-general mechanisms. In this experiment, children from kindergarten to second-grade were pretested in order to identify those who knew the win/block approach but had not yet learned the fork strategy. Because all children who participated in the rest of the experiment began with the same strategy, any age-related differences in learning that emerged were more likely to be the result of more general developmental differences in the use and efficacy of self-explanation and less likely to be the result of knowledge-based effects (although these can never be entirely ruled out).

## Overview of the Experiment

Children in both conditions participated in four phases: a pretest, studying example problems, a generalization posttest, and a recall posttest. In the pretest, kindergartners, first graders, and second graders were first tested to identify those who could play tic-tac-toe but did not yet know the fork strategy. Children who met these criteria were randomly assigned to either the *child-generated explanation* (CGE) condition or the *experimenter-generated explanation* (EGE) condition. In the CGE condition, children observed example games where one player used the fork strategy to win. Immediately after observing each move in the fork strategy, children were asked to explain why the move was smart. Children in the EGE condition observed the same example games; however, before each move in the fork strategy, the experimenter explained why the move children were about to see was a smart move. Then, after children saw the move, the experimenter asked them to explain why each move was smart. Thus, children in both conditions were asked to explain the example moves, but children in the CGE condition needed to generate the explanations entirely on their own whereas children in the EGE condition could repeat the explanation they had just heard the experimenter use. This was the only difference between the conditions throughout the experimental procedure.

After the example games, children were given a generalization posttest where they completed partially played tic-tac-toe games against a computer opponent. Each of these games could be won by forking. However, the moves needed to complete the fork were to different board locations than those demonstrated in the example games. Finally, in the recall posttest children were asked to replicate the exact sequence of moves they had observed in the example games.[1]

The three mechanisms through which explanations were hypothesized to aid generalization were assessed by three behavioral measures. To test whether explanations enhance generalization of strategies through increasing recall of them, we compared whether children who learned the correct explanation for the example strategy (regardless of their group) more often repeated all of the modeled moves during the recall posttest than children who had not learned the correct explanation. To test whether explanations

[1] There were several reasons why we did not include a third condition where children who did not observe the example games participated in the generalization posttest games. We did not include this control condition because prior studies suggest that the fork strategy is difficult for children to learn without help (Crowley & Siegler, 1993; Siegler & Crowley, 1994). In addition, pilot testing for the current study and a prior unpublished 10-week microgenetic study of kindergartners' tic-tac-toe found that spontaneous invention of the fork strategy is rare, at best. As described later, this is supported by the finding that even with the training provided in the current study, children generally found it very difficult to use the fork strategy on the generalization posttest games.

increase generalization through leading children to more often choose the strategy over alternatives, we examined whether children who learned the correct explanation for the example strategy more often produced initial moves consistent with the strategy in the generalization posttest games than did children who had not learned the correct explanation. To test whether explanations increase generalization through helping children more effectively manage the goal structure of the new strategy, we examined whether children who learned the correct explanation and who made the correct initial move in the generalization games were more likely to successfully complete the strategy than children who made the correct initial move but who had not learned the correct explanation.

## METHODS

### Participants

Participants were 34 kindergartners (*M* = 6.2 years, *SD* = .3 years), 40 first graders (*M* = 7.2 years, *SD* = .4 years), and 40 second graders (*M* = 8.2 years, *SD* = .4 years). As described below, an additional 15 children were pretested but did not meet participation criteria.

### Materials

A computer program was written to demonstrate example tic-tac-toe games and to play tic-tac-toe against the children. The program ran on a Macintosh equipped with a touch-sensitive screen that allowed children to interact with the program by simply touching the display.

When demonstrating example games, the program showed a play-by-play account of a game in which the X player used the fork strategy to win. During the demonstration, children were asked to predict each X move by touching the square where they thought the computer might go next. The program flashed the square the child had indicated before revealing the next X move. If the child predicted the move correctly, the computer played a digitized cartoon sound. If the child's prediction was wrong, the computer was silent.

The program followed a strategy designed to make it vulnerable to forking but otherwise invincible. Because the computer could only be beaten by a fork, children who knew the fork strategy had a strong incentive to use it, and children who did not know the strategy had a strong incentive to learn it. When children won, the pieces in the winning line flashed on and off while the computer played a series of digitized cartoon sounds. No sounds were played if the computer won or if the game ended in a tie.

### Procedure

The four-part procedure lasted approximately 20 minutes and was videotaped.

*Pretest.* Children were selected to participate if they knew how to make winning and blocking moves but did not yet know the fork strategy. To assess whether children knew how to win, the experimenter presented them a partially played tic-tac-toe game that the Xs could win on their next turn and asked them to make the move that would allow the Xs to win. To determine whether children knew how to block, the experimenter showed them a partially played game in which the X player needed to block on the next move to stop a potential O win and asked them to make the move that blocked the Os from winning. Four kindergartners, one first-grader, and one second-grader did not make both correct moves and were excluded from further participation.

Knowledge of the fork strategy was assessed by having children complete two examples of each of the boards shown in Figure 1. Children always went first and always played the Xs. In the two games corresponding to the leftmost board, they needed to make two moves to win via the fork strategy; in the games corresponding to the middle board, they needed to make three; and in the games corresponding to the rightmost board, they needed to make four. The program randomized the presentation order of the games for each child.

The logic of having children play games both from the beginning and from the middle was to maximize their opportunity to demonstrate competence. Children who knew how to fork might nonetheless find it difficult to execute the strategy from the beginning. Including games that children could win in only two or three moves reduced the possibility of children becoming distracted before they completed the fork strategy. However, the unfamiliar format of finishing partially played games might seem strange to children, and thus might interfere with their use of advanced strategies. Having them play typical games that started with blank boards controlled for this pos-

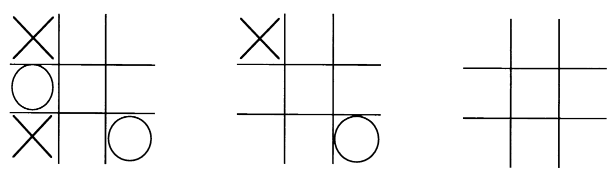


**Figure 1 Children completed two games from each of these three configurations on the pretest. To complete the fork, children had to make two moves in the left game, three moves in the middle game, and four moves in the right game.**

sibility. Together, the two types of games seemed to provide a more sensitive test for whether children knew how to fork than either type of game alone. Children were classified as knowing the fork strategy if they won at least one of the two full games or at least two of the four partial games. The criteria for the partial games was set at two rather than one win because of the relatively high (1 in 5) chance that random moves would have produced the correct fork move on the two games that began with five blank spaces remaining on the board. Three first graders and six second graders met this test and were excluded from further participation.

*Example games.* The fork strategy was demonstrated to children on four trials, with each trial consisting of a game in which they observed a player win by using the fork strategy and a game in which they tried to replicate the exact move sequence they had just observed. The X and O moves were the same on all four trials. The experimenter began by telling children that they would be watching tic-tac-toe games between Mr. Potato Head (a doll sitting on one side of the computer) and Bear (a stuffed animal sitting on the other side of the computer). Children were told that Mr. Potato Head was a very smart tic-tac-toe player and that if they watched how he played, they might be able to learn his smart tricks.

Figure 2 illustrates the procedure for the observation game. As children observed Mr. Potato Head win each time by forking, they were asked to predict be-

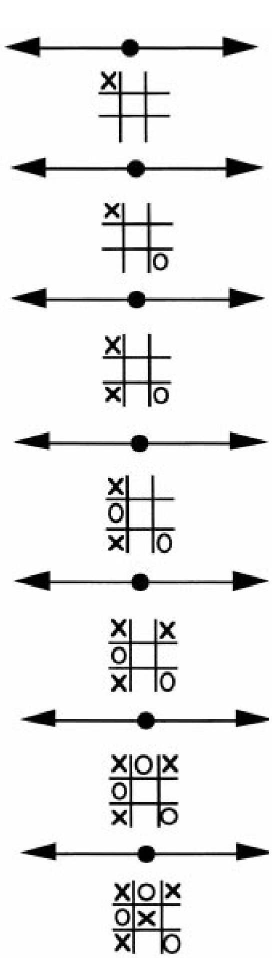
| Show Only | Example Game | Show and Example |
|---|---|---|
| Where will Mr. Potato Head put his first X? |  | Let me tell you about one smart trick that Mr. Potato Head uses when he plays Tic Tac Toe. He puts his Xs so that he has two ways to win at the same time. Then, even if Bear blocks one of the ways, Potato Head can still use the other way to win. Where will Mr. Potato Head put his first X? |
| Why did Mr. Potato Head put his X there? | | Why did Mr. Potato Head put his X there? |
| Where will Mr. Potato Head put his next X? | | Mr. Potato Head knows that on this next move it is very important that he goes to a corner if he wants to play his trick on Bear later on. Where will Mr. Potato Head put his next X? |
| Why did Mr. Potato Head put his X there? | | Why did Mr. Potato Head put his X there? |
| Where will Mr. Potato Head put his next X? | | Mr. Potato Head knows that on his next move he can put his X's so that he has two different ways to win. Then, even if Bear blocks one way, Potato Head can still win the game using the other way to win. Where will Mr. Potato Head put his next X? |
| Why did Mr. Potato Head put his X there? | | Why did Mr. Potato Head put his X there? |
| Where will Mr. Potato Head put his next X? | | Where will Mr. Potato Head put his next X? |

**Figure 2 The tic-tac-toe boards, from top to bottom, illustrate the move sequence children observed during learning-phase games. The questions and explanations for children in the experimenter-generated-explanation condition appear on the right; those for children in the child-generated-explanation condition appear on the left.**

fore each move where they thought he would go. After observing where the X was placed, they were asked to explain why Mr. Potato Head had gone there. Before observing each move, children in the EGE condition were told by the experimenter the logic of the fork strategy and of each move in it; children in the CGE condition did not receive this explanation. As can be seen by comparing Figures 1 and 2, the first, third, and fifth moves of the example game involved the exact configurations presented on the pretest.

After each observation game, children completed a replication game where they were asked to reproduce the exact same sequence of moves they had just observed Mr. Potato Head use. Children were asked to explain the reason for each of their moves in the replication game immediately after the move.

*Generalization posttest.* Children in both conditions played six games against the computer. Prior to the first game, children were told that Mr. Potato Head was taking a break and that they would now play some games against Bunny. The experimenter asked children to see if they could remember anything about Mr. Potato Head's trick that might help them win. In three games, two Xs and two Os were placed to create different rotations of the first four moves of the example game (top row of Figure 3). The other three games began with one X and one O placed on the board to create different rotations of the first two moves of the example game (bottom row of Figure 3). The program chose a random order of games independently for each child.

To demonstrate generalization of the fork strategy, children had to make moves that were logically equivalent to, but superficially different than, moves in the example games. If children learned the fork strategy by simply memorizing a sequence of moves, such transfer would be impossible. However, if they learned an appropriate explanation for the logic underlying the fork strategy, they might succeed in adapting their knowledge to the novel configurations.

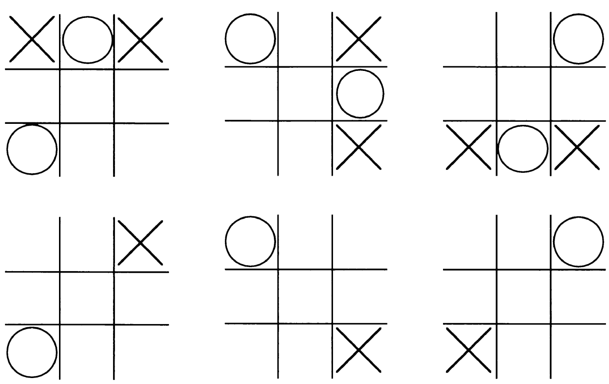


**Figure 3 The six opening configurations for the generalization games were rotations of 90°, 180°, and 270° of configurations that emerged during learning-phase games.**

*Recall posttest.* To conclude the session, children completed the same six games used to assess knowledge of forking on the pretest. Before they did so, the experimenter said that they should try to remember Mr. Potato Head's trick exactly as he had showed it to them. Completing the fork sequence in each type of game required that children make different numbers of moves, but the move sequence was identical—both at the logical and surface levels—to the move sequence of the example strategy. Thus, games in the recall posttest assessed whether children could recall the exact implementation of the fork strategy they had observed earlier. These games were included in order to identify whether any trouble children may have had using the fork strategy during the generalization games was due to difficulties in adapting their memory of the example moves to new game situations or simply due to the fact that children had forgotten the original example strategy. The games were presented in a different random order for each child.

## RESULTS

The results are presented in four parts. First, we consider what the pretest revealed about children's strategies when they began the study. Second, we analyze what children learned from the example games. Third, we examine use of the fork strategy during the generalization posttest. Fourth, we test the three hypotheses, described in the introduction, concerning how self-explanations exercise their effects.

### Pretest

As noted previously, the main goal of the pretest was to identify children who knew the win/block strategy but not the fork strategy. However, children's performance on the pretest also revealed their tendencies to make moves that may have facilitated or hindered acquisition of the fork strategy. The pretest games began from three configurations identical to those children would later encounter in the example games. In each of these configurations, setting up the fork strategy required a move to an open corner. If children's pretest performance revealed that they already preferred corner moves before they began the study, children might have found it easier to learn the fork strategy.

However, kindergartners, first graders, and second graders did not prefer corner moves (Figure 4). This

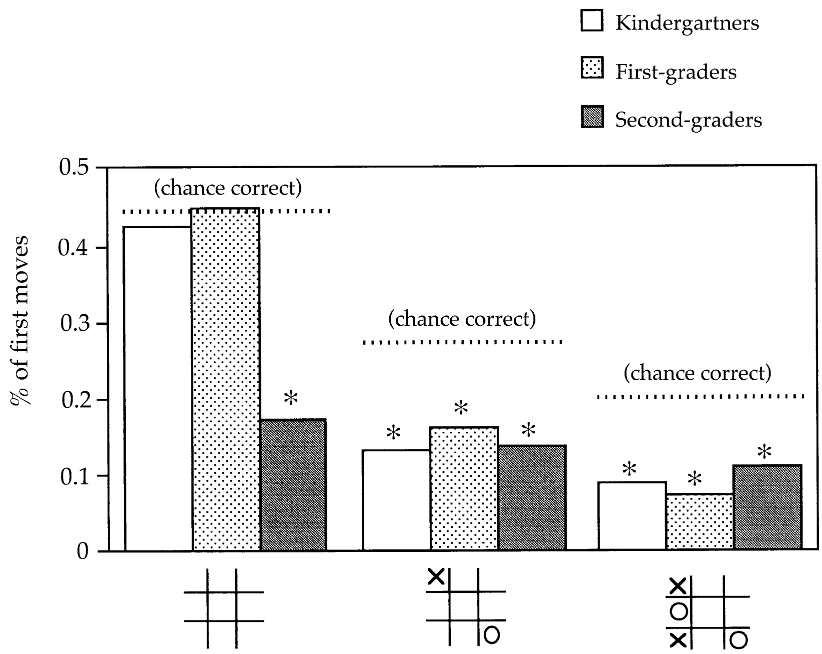



**Figure 4 Children did not show any preexisting preference for the moves necessary to implement the fork strategy. During the knowledge assessment games on the pretest, children moved to the required locations (corners) either at chance levels, or at levels significantly below chance (indicated by *).**

suggests that learning the fork strategy was not going to be a trivial task, because children's existing preferences did not directly support, and often conflicted with, the moves required to implement the strategy. In fact, if prior preferences had an impact, they may have made it *harder* for older children to learn the fork strategy. Kindergartners and first graders moved to corners no more often than chance on open boards, and less often than chance on boards that already contained some Xs and Os. However, second graders moved to corners less often than chance in all three situations. Thus, the most experienced tic-tac-toe players in the study exhibited move preferences that were in direct conflict with each of the first three moves in the strategy. (Additional analyses suggested that second-graders chose corners less often than chance because they were significantly more likely than chance to select moves to the middle. This is the best possible move for a child using the win/block strategy because a middle space is involved in more potential wins [or blocks] than any other location.)

Example Games

*Learning the moves of the fork strategy.* There were two converging measures of children's learning of moves in the fork strategy from examples. Each example trial consisted of a game where children observed the fork strategy and a game where they tried to replicate the strategy. In the observation games, children were asked to predict the location of each move before it occurred. In the replication games children were asked to make each move exactly as it had occurred in the observation games.

Findings from analysis of both predictions and replications converged on two conclusions: older children were more likely to learn the moves of the fork strategy, and experimental condition did not influence the probability of learning. A 3 $\times$ 2 (grade $\times$ condition) ANOVA on the number of games where the entire strategy was accurately predicted revealed only a significant main effect for grade, $F(2, 108) = 4.97$, $p < .01$. The effect of condition and the interaction were not significant, $F\text{s} < 0.7$. Scheffe tests suggested that second- and first-graders accurately predicted the strategy in almost half of the observation games (42% and 41%, respectively) whereas kindergartners (15%) predicted the strategy significantly less often.

Similarly, a 3 $\times$ 2 (grade $\times$ condition) ANOVA on the number of replication games where children reproduced the entire fork strategy revealed only a significant main effect for grade, $F(2, 108) = 3.36$, $p < .05$. The effect of condition and the interaction were not significant, $F\text{s} < 0.9$. Second-graders replicated the strategy in 56% of games; first-graders in 51%; and kindergartners in 34%. Scheffe tests revealed that only the difference between second-graders and kindergartners was significant.

*Learning the fork explanation.* Children were asked to explain moves in both the observation and replication games. Children were coded as knowing the fork explanation if they explained a move in terms of simultaneously setting up two potential winning paths. Reliability was determined by having a second rater score 20% of the data; the raters agreed on 94% of classifications.

A 3 × 2 (grade × condition) ANOVA on the number of observation games in which children used fork explanations revealed main effects for grade, $F(2, 108) = 9.72$, $p < .0001$, and condition, $F(1, 108) = 10.11$, $p < .01$. The interaction was not significant, $F < .2$. Older children and children in the EGE condition were the most likely to learn the fork explanation. Second-graders in the EGE condition used fork explanations in 66% of games compared to 50% for those in the CGE condition; first-graders in the EGE and CGE condition used fork explanations in 51% and 28% of games, respectively; kindergartners in the EGE and CGE conditions used fork explanations in 34% and 13% of games, respectively. Scheffe tests of the effect for grade revealed that second-graders used more fork explanations than kindergartners ($p < .0001$) and marginally more than first graders ($p = .05$).

A 3 × 2 (grade × condition) ANOVA on the number of replication games in which children used fork explanations also revealed a main effect for grade, $F(2, 108) = 8.77$, $p < .001$. The effect of condition and the interaction were not significant, $F$s $< 1.7$. Fork explanations were used in 50% of replication games by EGE second-graders and 53% of games by the CGE second-graders, 38% of games by EGE first-graders and 28% of games by CGE first-graders, and 25% of games by EGE kindergartners and 6% of games by CGE kindergartners. Scheffe tests revealed that differences between second-graders and kindergartners were significant ($p < .001$) and between second-graders and first-graders were marginally significant ($p = .08$).

Why was the effect of condition significant for the observation games but not the replication games? Recall that the manipulation of providing explanatory help occurred only during observation games. In replication games children in both conditions were explaining their own moves without help from the experimenter. Thus, it is not surprising that the effect of condition was found to be muted in the replication games.

### Generalization Posttest

To win a game in the generalization posttest children needed to make moves that were logically equivalent to those of the example strategy but that were to different board locations. Because the computer opponent was vulnerable to forking but otherwise invincible, the proportion of wins in the generalization posttest games equaled the proportion of games in which children correctly executed a fork strategy.

Children found it difficult to generalize the fork strategy, winning only 33% of generalization posttest games. A 3 × 2 (grade × condition) ANOVA revealed a main effect for grade, $F(2, 108) = 6.24$, $p < .01$. The effect of condition and the interaction were not significant, $F$s $< .8$. Second graders were the most successful (45% wins), followed by first graders (26%) and kindergartners (16%). Scheffe tests revealed that the difference between the second-graders and kindergartners was significant and that the difference between second- and first-graders was marginally significant, $p = .07$.

At this relatively general level of analysis, results seemed consistent with the oft-replicated finding that if older and younger children are exposed to the same instruction, older children show wider generalization (e.g., Schneider & Pressley, 1989). However, further analyses revealed more complex relations among age, learning from examples, and generalization.

When studying the example games, older children were more likely than younger ones to have learned the moves of the fork strategy and to have learned the fork explanation. This greater initial learning, rather than general developmental differences in generalization ability per se, could have produced the older children's greater use of forking on the novel configurations. If this was true, younger and older children who came to the generalization games with equal levels of knowledge about the fork strategy should have been equally successful in using the strategy.

A stepwise regression analysis was conducted to test this possibility. It included four predictors of generalization: age, experimental condition, the number of correct predictions and correct replications of the fork strategy during the example games, and the number of observation and replication games explained as a fork. The last two predictors are composites of the converging measures of performance on the example and replication games; the regression results did not change when only example or only replication games were included as predictors.

The regression analysis revealed that age-related differences in generalization were best explained as age-related differences in initial learning. The only variables accounting for significant independent variance were the number of correct predictions and replications of the fork strategy and the number of games explained as forks. Together, the two measures accounted for 32% of the variance in the number of generalization problems on which the fork strategy was successfully used, $F(2, 113) = 25.96$, $p < .0001$. Once these two variables had been accounted for, age and condition were essentially uncorrelated with generalization (partial *r*s = .11 and −.05, respectively). Thus, younger children who learned the same amount as older children from the examples were as effective as the older children at generalizing the fork strategy to new game situations. Similarly, children who had learned the fork explanation from the experimenter generalized just as effectively as children who had generated the fork explanation by themselves.

Did children need to learn both the moves and the explanation in order to generalize? To explore this question, children were divided into four learning categories: (1) children who learned the move sequence (at least one correct prediction or replication of the entire fork sequence during the example trials) and the fork explanation (at least one observation or replication game explained as a fork), (2) children who learned the moves only, (3) children who learned the fork explanation only, or (4) children who did neither.

Findings suggested that generalization occurred primarily among the children who learned both the moves and the fork explanation. A 4 × 3 × 2 (learning category × grade × condition) ANOVA on the number of wins in the generalization posttest games revealed only an effect for learning category, $F(3, 91) = 8.44$, $p < .001$. The effects of grade and condition and all interactions were not significant, *F*s < .6. Scheffe tests indicated that the main effect for learning category was due to children who learned both moves and explanations winning significantly more often ($M$ = 48% wins) than children in any other category. There were no differences in the mean number of wins among children who learned only the moves ($M$ = 15%), only the fork explanation ($M$ = 7%), or neither ($M$ = 3%).

## Testing the Three Hypotheses

We now consider the three hypothesized mechanisms through which learning explanations could increase generalization: (1) explanations increase recall of the example strategies; (2) explanations increase selection of the strategy; and (3) explanations improve subgoal management during execution of the strategy.

To test the three hypotheses, we compared children on three measures:

1. Given that children had initially learned the moves of the example strategy (measured by at least one accurate prediction or replication of the strategy during example games), what was the probability that children maintained a memory of the example strategy throughout the rest of the study (measured by at least one win during the recall posttest).
2. Given that children remembered the example strategy, what was the probability of choosing to use the strategy in a generalization posttest game (measured by making the correct first move in at least one such game).
3. Given that children remembered the strategy and chose to use it, what was the probability of satisfying all necessary subgoals (measured by at least one win in a generalization game).

Because prior analyses showed that grade and condition were unrelated to strategy generalization once learning had been taken into account, we did not include these variables in the reported analyses.

Figure 5 illustrates the paths to successful generalization of the fork strategy. The left-side path depicts the performance of children who used a fork explanation at least once during the example trials. The right-side path depicts the performance of children who did not use a fork explanation.

As shown at the top of the diagram, most children

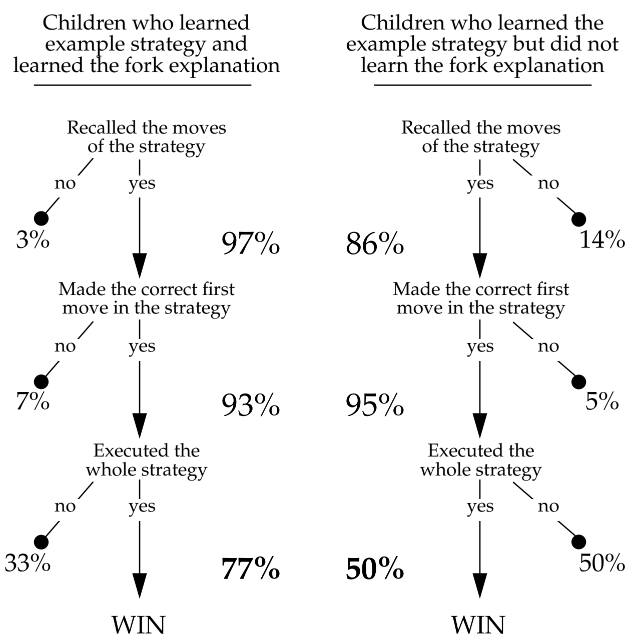



**Figure 5** **Regardless of whether they knew the fork explanation, children who memorized the move sequence for the strategy were likely to remember it and to begin to execute it. However, children who knew the fork explanation were more likely to execute the entire strategy successfully and to win the game.**

who learned the moves for the example strategy maintained a memory of those moves throughout the generalization games. Of the 62 children who learned the moves and the explanation for example strategy, 60 correctly reproduced the example strategy at least once during the recall posttest games. Similarly, 19 of the 22 children who learned the moves but not the fork explanation correctly reproduced the example strategy in at least one of the recall posttest games. The difference between the two groups of children was marginally significant, $\chi^2(1, N = 84) = 3.14, p = .08$.

As shown in the middle of the diagram, children who remembered the example strategy were also very likely to try to adapt the example strategy in at least one generalization posttest game. Of the 60 children who learned to reproduce the example strategy, learned the fork explanation, and remembered the example strategy, 56 made a first move consistent with the fork strategy during at least one of the generalization posttest games. Of the 19 children who learned to reproduce the example strategy, did not learn the fork explanation, and remembered the example strategy, 18 chose to use the strategy during the generalization posttest games, $\chi^2(1, N = 79) = .05, p = .8$.

Finally, the bottom of the diagram shows that knowing the fork explanation made a difference in whether children who began the fork strategy during the generalization posttest games were successful at executing the entire strategy and winning the game. Of the 56 children who had learned the example strategy, learned the fork explanation, remembered the example strategy, and tried to use the fork strategy during the generalization posttest games, 43 went on to successfully execute the entire strategy and win at least one generalization posttest game. However, of the 18 children who had learned the example strategy, not learned the fork explanation, remembered the example strategy, and tried to use the fork strategy during the generalization posttest games, only 9 went on to successfully execute the entire strategy and win at least one generalization posttest game, $\chi^2(1, N = 74) = 4.68, p < .05$.

These findings were accentuated when the analyses were redone with two rather than one instance of each outcome used as the selection criterion. The direction of all three findings remained the same, whereas small differences for remembering the strategy moved from marginal to non-significant, $\chi^2(1, N = 84) = 1.1, p = .3$, and the difference for fully executing the strategy became more pronounced, $\chi^2(1, N = 58) = 7.84, p < .01$.

Thus, there were two main findings. First, children who failed to generalize were most often diverted from the solution path after the point at which they had already begun using the fork strategy. Second, children who knew the fork explanation were more likely to bring an initiated fork strategy to successful conclusion than children who did not know the fork explanation.

## DISCUSSION

This study tested three hypothesized mechanisms through which explanations might facilitate children's generalization of a newly learned strategy: more accurate recall of the strategy's procedures; increased selection of the new strategy over preexisting strategies; or more effective navigation through the new strategy's subgoal stack. Findings supported the third hypothesis. Regardless of whether children knew the explanation for the novel strategy, children who had initially memorized the moves of the strategy almost always recalled them and chose to begin using the new strategy during the generalization posttest games. However, as the games progressed and children needed to respond to the computer's moves, children who knew the explanation were better able to resist the temptation of abandoning the new approach in favor of defensive moves or simpler offensive approaches.

Why did explanations help children resist the temptation to abandon the new strategy in mid-execution? Consider why children might switch to other approaches. In tic-tac-toe, as in many social problem-solving contexts, success demands that an individual's strategies be flexible enough to accommodate the unexpected consequences of the strategies used by those around them (Crowley & Siegler, 1993; Thagard, 1992). The successful tic-tac-toe strategy user simultaneously monitors her progress towards the goal of winning the game and the goal of not losing it. As described earlier, children using the win/block strategy coordinate offensive and defensive goals by making decisions according to a subgoal hierarchy in which they first look for winning opportunities, then look for blocking opportunities, and finally look for open locations that would help them set up winning opportunities.

Children who did not learn the fork explanation appeared to graft the new moves of the strategy onto the existing subgoal hierarchy of the win/block strategy. When interpreted in terms of the logic of the win/block strategy, the fork sequence would not be seen as a novel way to guarantee a victory but as a particular series of attempts to set up an opportunity to win. Consistent with this interpretation, children who did not know the fork explanation often explained the success of the example strategy by saying that the O player caused the losses by not paying enough attention or that the X player kept winning because he was very lucky.

How would grafting the new moves onto the win/block goal structure lead to children abandoning the fork strategy during generalization games? Recall from Figure 3 that on each of the opening moves in the generalization posttest games, the Xs immediately set up at least one way to win the game. In the fork strategy, forcing your opponent to make these blocks is a key element in seizing the initiative. However, in the win/block strategy, a blocked winning path is a signal to abandon the current direction and return to scouring the board for other offensive and defensive opportunities. Thus, when children who were using the win/block goal structure set up an early opportunity to win, only to have it blocked by their opponent, they saw the block as an impasse, rather than as a sign that an essential subgoal had been satisfied. After this impasse, children using the win/block strategy would expand the number of potential locations they would consider on their next move. All open-board locations would be competing with each other to be involved in the next direction the child chose to pursue. The pretest showed that the corner moves required by the fork strategy were generally not strong competitors before children began the study; it should not be surprising that corner moves often lost out in open competition and that children who did not know the fork explanation often abandoned the strategy in mid-execution.

In contrast, children who learned the fork explanation created a new goal structure that allowed them to correctly interpret the early blocks as part of the normal progression of the strategy. By creating a rationale for each move, the explanation enabled children to view each one as a subgoal in service of a larger goal and to accurately assess whether each successive subgoal had been satisfied. Rather than signaling an impasse, the early blocks provided positive feedback that children were on track to reach their ultimate goal. Rather than the computer's blocking move increasing the appeal of competing moves, it would decrease it. Thus, understanding why the fork strategy worked may have guided children through systematically meeting its subgoals and may have helped them resist the temptation to abandon the new strategy and return to a more familiar approach.

This study extended prior work on self-explanation by testing whether the facilitative effect of explanation depends on the content or the source of the explanation. In this study, generalization was facilitated when children knew the content of the fork explanation, regardless of whether they generated the explanation themselves or learned it from the experimenter. This finding has immediate practical implications for formal and informal education, because it suggests that there may be little value-added in requiring children to construct explanations entirely on their own as opposed to having a teacher, computer tutor, peer-tutor, or parent provide explanatory help. Both in formal (Anderson, Reder, & Simon, 1996; Rogoff, Matusov, & White, 1996) and informal learning educational settings (Crowley & Callanan, 1998) there have been debates about the relative merits of discovered versus instructed conceptual knowledge. The current findings suggest that knowing the right explanation is what makes learning powerful, regardless of where the explanation came from. This conclusion is generally consistent with the broader literature on coconstruction of knowledge during collaborative problem-solving and expert teaching (e.g., Azmitia, 1996; Dunbar, 1995; Leinhardt & Schwarz, 1997; Okada & Simon, 1997).

The study also provided a direct test of possible age-related differences in the facilitative effect of explanations. Although older children were more likely than younger children to learn the fork explanation, younger and older children who learned it subsequently generalized equally effectively. These findings—consistent with prior studies of children's analogical reasoning (e.g., Brown, Kane, & Echols, 1986)—support the notion that there is not a general age-related difference in children's generalization mechanisms. Younger children may be less likely to generalize new problem-solving strategies simply because they are less likely to learn good explanations for them.

Why were younger children less likely than older children to learn the fork explanation? Adults have been hypothesized to construct new explanations when they perceive mismatches between their expectations and the outcomes they observe (VanLehn, Jones, & Chi, 1995). Age-related differences in children's expectations for tic-tac-toe may explain why older children in the current study were more likely than younger children to learn the fork explanation. Although kindergartners, first graders, and second graders began this study using the same win/block strategy, second graders are typically expert enough to detect almost all blocking opportunities whereas kindergartners detect only about half (Crowley & Siegler, 1993). Thus, two second graders using the win/block strategy would consistently play to a draw, but two kindergartners would often exchange wins and losses as well as draws. Faced with an opponent who uses the fork strategy, however, second graders can block at every opportunity and still lose the game.

The mismatch between strongly expecting a draw but then seeing a loss in the example games could lead second graders to quickly recognize that their existing explanations could not account for what they were observing. In contrast, kindergartners, who are more used to losing, might view the example games as typical, and not see any immediate need to revise their current goal structure.

Older children may also have been more likely to learn the fork explanation because their greater experience with tic-tac-toe had enabled them to develop a "goal-sketch" for the fork strategy. In domains where children have at least moderate problem-solving experience, they sometimes acquire enough general knowledge of the goal structure of a domain to allow them to recognize why a novel strategy is effective even before they learn how to use the novel strategy (Siegler & Crowley, 1994; Siegler & Jenkins, 1989). An important characteristic of socially contextualized domains such as tic-tac-toe is that children often are exposed to advanced strategies long before they begin to use the strategies themselves. In the present study, most children probably had experience losing tic-tac-toe games to an advanced peer, older sibling, or parent who used the fork strategy. These losses may have helped children begin to recognize that there is a more advanced approach than the win/block strategy, even though they themselves did not know how to implement the new strategy. When presented with the repeated examples and repeated requests for explanation in the current study, older children may have capitalized on their greater familiarity to encode the examples and construct explanations more efficiently.

Tic-tac-toe requires adaptive, on-the-fly adjustment of strategies to respond flexibly to unfolding circumstances (Crowley & Siegler, 1993), a characteristic shared by many everyday activities (Rogoff, 1990; Rogoff, Gauvain, & Gardner, 1987; Thagard, 1992). Although our findings support the conclusion that explanations helped children execute the new strategy in the face of this uncertainty, further research is needed to determine how explanations facilitate generalization in domains with other characteristics. For example, simple arithmetic is a domain involving fiercer competition at the point of strategy selection than tic-tac-toe; however, once selected, arithmetic strategies are less likely than tic-tac-toe strategies to be abandoned in mid-execution (Siegler & Jenkins, 1989). Accordingly, in the case of simple arithmetic we have hypothesized that explanations serve primarily to tilt strategy selection in favor of newly acquired strategies (Crowley, Shrager, & Siegler, 1997). This is not inconsistent with the current findings. Much (perhaps most) of the variance observed in human behavior stems from the tasks in which we engage (Simon, 1981). The full story of how explanations facilitate strategy generalization will only be told through examination of a broad range of tasks and domains.

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