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Cognitive Load, Schema Acquisition, and Procedural Adaptation in Nonisomorphic Analogical Transfer

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Cognitive load theory was explored in three conditions among 96 3rd graders in nonisomorphic transfer. In one condition, both goal attainment and problem-space exploration were emphasized on each acquisition trial. In a 2nd condition, problem-space exploration was emphasized, whereas goal attainment was not. In a 3rd condition, goal attainment was emphasized, but the problem space was explored only until an error occurred on each trial. All children solved 2 analogues of the missionaries/cannibals problem and transferred to an analogue of the jealous husbands problem. Children in the 2nd condition made fewer errors and required less time than the other groups on the 1st move in transfer, which is taken to reflect the quality of the base attained during acquisition. On later moves, children in Conditions 1 and 2 outperformed those in Condition 3. Thus, children in the first two conditions were better able to adjust the base to the target.

The application of existing knowledge to new but related problems has been a topic of continuing interest to psychologists throughout the 20th century. Historically, this kind of application, called *analogical transfer,* has been studied under a variety of labels. The theoretical frameworks have ranged from Titchener's (1910) to Piaget's (e.g., Inhelder & Piaget, 1958) structuralism and from functionalism (e.g., Thorndike, 1923; Thorndike & Woodworth, 1901) and behaviorism (e.g., Cantor, 1965; Hull, 1939; Spence, 1937) to Gestalt psychology (Duncker, 1945; Luchins, 1942; Sobel, 1939), in addition to some that resist easy classification (e.g., Judd, 1908; Spearman, 1923). In the context of modern cognitive psychology, most recent work on analogical transfer, including that reported below, has involved problem solving (Burstein, 1986; Carbonell, 1986; Holyoak, 1984; Holyoak & Thagard, 1989; Reed, 1987; Reed, Dempster, & Ettinger, 1985; Reed, Ernst, & Banerji, 1974; Ross, 1984, 1987, 1989), with an emphasis on the transfer of knowledge organized structurally into frames or schemas (Brown, Kane, & Echols, 1986; Gentner, 1983, 1989; Gholson, Morgan, Dattel, & Pierce, 1990; Gick & Holyoak, 1980, 1983; Sweller, 1988, 1989).

To provide a context for the present research, we begin by describing the component processes required for successful transfer between *isomorphic* problems, that is, transfer between problems with identical goal structures, constraints, and problem spaces (Gholson, Eymard, Morgan, & Kamhi, 1987). First, the solution to the original problem, or *base,* must be learned and represented in terms of its generalizable structural relations (Brown et al., 1986; Gentner, 1983; Holyoak, 1984) rather than in terms of specific surface details, such as object attributes. Second, the correspondence between the known solution (base) and the new problem (target) must be noticed (Ross, 1984, 1987). Third, the base must be retrieved in terms of its relational structure (Gentner, 1983; Reed, 1987). Finally, the same relations that hold among objects in the base are applied to objects in the target. This mapping process has the effect of placing the objects in the base and target in one-to-one correspondence, as a result of the roles they play in a common relational structure (Gentner, 1989, p. 201; see also, Holyoak & Thagard, 1989; Palmer, 1989).

If, however, the target problem is not isomorphic to the base (i.e., is nonisomorphic), then the four processes described in the preceding paragraph do not provide a complete account of what is necessary for successful analogical transfer. In general, when a given base is applied to a nonisomorphic target problem, the initial mapping is, by definition, incomplete. That is, when there is not a one-to-one correspondence between structural features of the base and the target, a complete mapping is not possible. Additional processes, which Novick (1988) dubbed "procedural adaptation" (p. 511) are required to bring a nonisomorphic base and target into correspondence. That is, one replaces any operators in the original base that would lead to illegal problem states, or that would fail to produce progress toward the goal, with new operators that are adapted to the demands of the target.

Ideally, when procedural adaptation is required, both the base and the target problems are represented correctly, in terms of their structural features, at the outset. One then notes the differences and modifies the procedures in the base (see Carbonell, 1986, pp. 144–145), making whatever changes are needed to yield a one-to-one mapping between the (now modified) base and target. In practice, however, other possibilities might also be expected to occur, at least in complex problem-solving tasks (Gholson, Dattel, Morgan, & Eymard, 1989). One might, for example, recognize

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at the outset that a one-to-one mapping is not possible but be unable to produce the modifications necessary to bring procedures in the base into correspondence with the target. Any further attempts at procedural adaptation would then be expected to take place while the problem-solving activities themselves are being carried out. Initial difficulties in mapping the base to the target would be expected to result primarily in an increase in the time required on the first move and/or the error rate on that move. Later difficulties in carrying out procedural adaptation during the course of problem solving would be expected to increase the time or error rate on later moves, although at present there is no principled way of predicting the specific move or moves on which this should occur.

When subjects exhibit successful analogical transfer between a nonisomorphic base and target, then one may reasonably assume that several conditions have been met: First, the (partial) correspondence between the base and target was noticed. Second, a high-quality base was available and was retrieved. Third, the base was mapped to the target. Fourth, some procedures in the base were modified to bring them into one-to-one correspondence with the target. When subjects fail to exhibit successful transfer, however, it is not always clear which component process or processes failed (e.g., Brown, 1989; Brown et al., 1986; Gholson et al., 1990; Gick & Holyoak, 1980, 1983; Novick, 1988; Reed, 1987; Reed et al., 1974, 1985; Ross, 1984, 1987; Simon & Reed, 1976).

In a fairly typical series of experiments, Reed et al. (1974) studied both isomorphic and nonisomorphic transfer in standard versions of the missionaries/cannibals (MC) and jealous husbands (Jh) scheduling problems, each requiring a minimum of 11 moves for solution. In each problem, six characters, three of each of two types, must cross a barrier in a vehicle that can contain no more than two characters and must contain at least one character on each crossing. In MC the cannibals (Cs) may never outnumber the missionaries (Ms) on either side of the barrier. In Jh no wife (W) may be in the presence of any man unless her husband (H) is also present. Because there is no way to distinguish any one M (or C) from another, there are only four distinct 11-move solution paths in MC. However, the Hs (and Ws) are nonequivalent in Jh, and thus this task yields 486 distinct 11-move solution paths. If Ws are substituted for Cs and Hs are substituted for Ms, however, each of the latter solution paths will map directly onto one of the four paths in MC, resulting in a many-to-one (or homomorphic) mapping.

The young adults studied by Reed et al. (1974) failed to show nonisomorphic transfer. Even in isomorphic transfer, these subjects failed to show improvement in terms of the total number of moves to solution, although there was some reduction in the total time required and in the number of illegal problem states exhibited. In related work involving isomorphic transfer between MC problems, Simon and Reed (1976) also obtained disappointing results (see also Greeno, 1974; Reed & Johnsen, 1977). In fact, failure to obtain successful transfer has not been an uncommon finding in research on analogical reasoning in a variety of problem domains (e.g., Gholson, Eymard, Long, Morgan, & Leeming, 1988; Gick & Holyoak, 1980, 1983; Guberman & Greenfield, 1991; Novick, 1988; Reed, 1987; Reed et al., 1985; Rogoff & Gardner, 1984; Ross, 1984, 1987).

In attempting to address the many instances of (analogical) transfer failure, Sweller (1988, 1989) suggested that the findings frequently result from events that transpire prior to transfer. That is, because of conditions that prevail during original learning, the base that is acquired—and eventually transferred to the target problem—is of poor quality. Support for this claim is derived from what Sweller (1988, 1989) called "cognitive load" theory, which says that "some forms of problem solving interfere with learning" (Sweller, 1988, p. 257), as do some instructional formats (Sweller, Chandler, Tierney, & Cooper, 1990). According to cognitive load theory, conventional problem solving, which emphasizes goal attainment, leads subjects to use means/ends analysis. Because the means/ends analysis involves working backward from the goal, it overloads processing capacity, leaving few resources for schema acquisition (i.e., for learning). Means/ends analysis is resource demanding because, when working backward from the goal, subjects (a) split their attention between the current state and the goal state to determine what the differences are, while (b) simultaneously searching among the available move operators in an attempt to select one that will reduce this discrepancy on their next move. Thus, the relationship between consecutive problem states and required operators is of secondary concern. However, according to cognitive load theory, the kind of learning that maximizes schema acquisition requires direct exploration of the problem space and the move operators for the problem solver to see what moves are possible. That is, efficient schema acquisition necessitates attention to the relationship between classes of problem states and operators.

Thus, an implication of cognitive load theory (Sweller, 1988, 1989) is that an increased emphasis on goal attainment during original learning should actually decrease schema acquisition, thereby significantly reducing the quality of transfer. This is because the greater the emphasis on goal attainment, the higher is the likelihood that problem solvers will engage in means/ends analysis; that is, they will work backward from the goal. Working backward has two interrelated outcomes that may inhibit schema acquisition. First, as indicated in the previous paragraph, means/ends analysis involves a variety of cognitive activities that are resource demanding. Second, because these activities absorb cognitive capacities, few resources are available for schema acquisition (Sweller, 1988, 1989).

In the present research, we used three instructional formats, designed to manipulate the amount of problem-space exploration and the emphasis on goal attainment, to study nonisomorphic analogical transfer in somewhat simplified (7-move) versions of MC and Jh problems that are appropriate for use with elementary school children (Gholson et al., 1989, 1990). In MC there are three Ms and two Cs. In Jh two Ws are paired with their respective Hs, and a third woman is included whose location is unconstrained. With the exception of the unpaired, third woman in Jh, the problem constraints are the same as those in the MC and Jh problems used by Reed et al. (1974). That is, Cs may never outnumber Ms on either side of a barrier in MC, and in Jh neither W may be in the presence of any man unless her own H is present. The goal is to get all five characters across a barrier in a vehicle that can carry at most two and must carry at least one individual on each crossing. In acquisition, the children were presented with the MC problem, which as may be seen in Figure 1, includes only nine different 7-move solution paths in its problem space. All children transferred to the Jh problem, which has a much larger problem space, with 238 identifiable 7-move solution paths.

Method

Subjects

The subjects were 96 third graders, of which 32 were assigned to each of the three instructional conditions. However, the data of 2 children were lost due to equipment failure, so only 94 were included in the analyses reported below. There were 31 children in two of the conditions and 32 in the third. Approximately equal proportions of boys and girls and of Black and White children were assigned to each group. Each child was tested individually in a single session lasting about 30 min, and a video recorder that

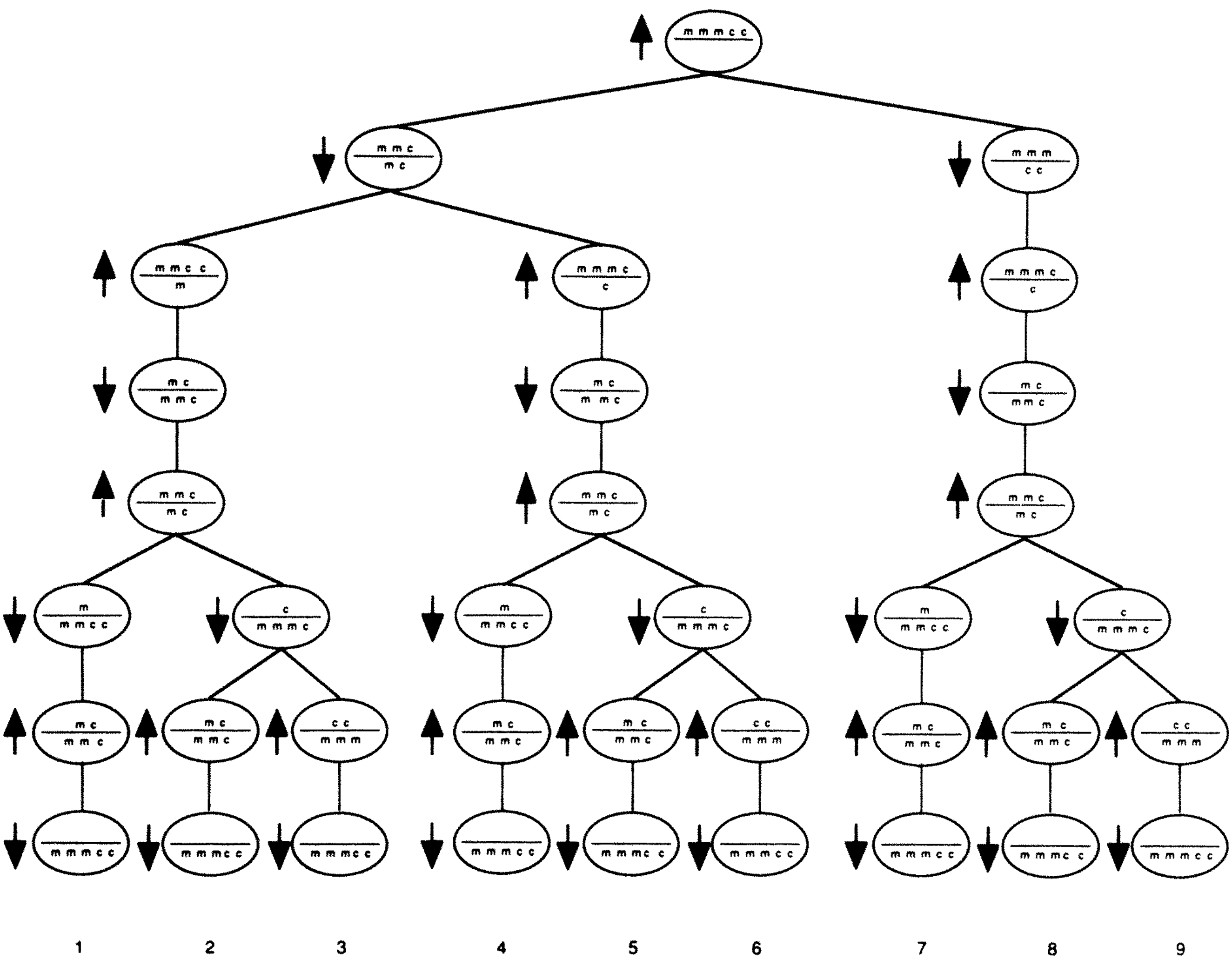

Figure 1. The nine 7-move solution paths in the problem space of the missionaries/cannibals problem, represented as connected nodes; the problem cannot be solved in fewer than 7 moves. (The Ms and Cs represent missionaries and cannibals, respectively. The line bisecting each oval represents the barrier, and the arrowheads point to the location of the vehicle at that node. From "Problem solving, recall, and mapping relations in isomorphic transfer and nonisomorphic transfer among preschoolers and elementary-school children" by B. Gholson, A. R. Dattel, D. Morgan, and L. A. Eymard, 1989, *Child Development, 60,* p. 1174. Copyright 1989 by the Society for Research in Child Development, Inc. Adapted by permission.)

displayed time accurate to decaseconds was used to record each child's entire session.

Design and Instructional Procedure

During base acquisition, the children in all three instructional conditions solved each of two consecutive analogues of the MC problem. The analogues, which involved cartoon-type characters (e.g., see Appendix), were called "ewoks and pilots" and "dreadnocks and GI's." The ewoks and dreadnocks played the roles of cannibals in their respective problems. Half of the children in each instructional condition received the ewoks and pilots analogue first, and for the other half, the order was reversed. Two parts composed the acquisition criterion. The children in each condition received their first analogue on repeated trials until they exhibited an error-free, 7-move solution (see the nine paths in Figure 1). The second analogue was then presented on repeated trials until a 7-move error-free solution was attained. Problem constraints were described to the children in all three instructional conditions at the outset of each trial (see Appendix). Because the acquisition criterion was the same in all conditions, we interpret any differences obtained in transfer as reflecting the learning that resulted from the different instructional procedures.

As indicated in the preceding paragraph, problem constraints were described to all subjects at the outset of each trial. Immediately after the constraints were described, half of the children in each instructional condition were presented with physical materials representing the problem (e.g., two ewoks, three pilots, river, boat, air base) and asked to show how to get everyone across the barrier safely. The remaining half of the children in each instructional condition were given an explicit solution to the problem before they were asked to solve it. That is, on each trial, after the constraint information was presented, these children were read a list of seven story units describing a series of moves that, if followed correctly, would lead to problem solution in 7 (error-free) moves. The series of moves corresponded to the first solution path in Figure 1, the path on the far left side.[1] We hypothesized that providing solution information in this way during base acquisition might interfere with transfer. The rationale for this prediction was that if the children attempted to maintain the seven story units in memory during problem solving, the memory demands might absorb processing capacity and interfere with schema acquisition. However, because there was no hint of any effect in transfer (see Results and Discussion section), and because the prediction was not derived from cognitive load theory, we did not consider it further.[2] Immediately after the list of moves was read, the physical materials, which were placed behind a screen when not in use, were produced and the child was asked to show how to get everyone across the barrier safely.

Correct and continue. In one acquisition condition, dubbed correct and continue (C&C) in this study, any time the children made an error, either by moving objects into an illegal problem state or by making an illegal move (e.g., moving three or more characters simultaneously), the experimenter stopped the problem-solving activity, explained the constraint violation in the context of the problem configuration in which it occurred, moved the object or objects to the locations they occupied before the error occurred, and requested a new move. To proceed from any one problem state to the next, the children were required to exhibit a legal move that resulted in a legal problem state. A given trial was terminated only when all five characters were in the goal state, and trials of this type continued until the acquisition criterion was attained. Thus, this procedure was designed to facilitate problem-space exploration and to emphasize goal attainment.

Although the children were required to exhibit a constraint-consistent move at each problem state on each trial, according to cognitive-load theory schema acquisition should be incomplete. This is because the theory predicts that, as a result of the emphasis on goal attainment, the children should be very likely to engage in resource-demanding means/ends analysis. That is, the children were expected to divide their attentional resources among the current state, the goal state, the difference between the two, and a search among available operators for one that reduces the discrepancy. In ideal schema acquisition, however, the focus of attention is on the associative relationship between each current state and the required move operator.

Explore. In a second condition, called explore (EXP), there was much less emphasis on goal attainment. The children were, of course, told the problem constraints at the outset of each trial, but they were otherwise permitted unconstrained exploration of the problem space. That is, the children were permitted to move characters in any manner they chose until all five were in the goal state. If one or more errors occurred during any given trial, then after all five characters were in the goal state, the first error was corrected. To correct the error, the experimenter first reconstructed the problem configuration that contained the constraint violation and then explained why it was an error. No other errors were corrected on that trial. Trials of this type continued until the acquisition criterion was met on each of the two consecutive analogues. Thus, EXP and C&C were similar in that problem-space exploration continued until all five characters were in the goal state on each precriterion trial. The two conditions differed, however, with respect to emphasis on goal attainment. Goal attainment was emphasized in C&C by requiring the children to make a legal move at each problem state, with errors immediately corrected. In EXP, however, goal attainment was not emphasized because all moves were accepted, including errors. According to cognitive load theory, because goal attainment was emphasized in C&C but not in EXP, children in the EXP condition should acquire a schema of higher quality, thereby exhibiting more successful analogical transfer than children in C&C.[3]

Trial terminate. In a third condition called trial terminate (TT), the children were permitted to proceed through the problem space only until an error occurred. That is, when the children made an error, it was immediately explained in the context of the problem configuration in which the violation occurred, but all five characters were then removed and a new trial was begun. Thus, in both EXP and TT, only the first error was corrected, but in TT the trial was terminated when the error occurred, whereas

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[1] The children were not required to exhibit any particular path on criterion trials; that is, any of the nine 7-move (error-free) solutions was accepted (see Figure 1) on each analogue.

[2] An alternative possibility was that transfer might be impaired if the children attained the acquisition criterion in fewer trials and thus had less opportunity to practice and explore problem states. The children for whom solution information was provided during acquisition did learn faster on the first analogue (see Results and Discussion section), but there was no effect on the second analogue, and in transfer there was no hint of any main effect or interaction involving this variable.

[3] It could be argued that because children in the different conditions explored the problem space in different ways during acquisition, they were actually exploring somewhat different problem spaces. This may be correct, but the same would hold in much of the research on problem solving that is designed to compare the effects of different acquisition conditions (e.g., Kotovsky & Fallside, 1989; Kotovsky, Hayes, & Simon, 1985; Reed, 1987).

in EXP the children continued to explore the problem space until all five characters were in the goal state on each precriterion trial. According to cognitive load theory, children in the TT condition were at a double disadvantage in comparison with those in EXP. First, goal attainment was emphasized in TT—as it was in C&C—which should promote the use of means/ends analysis. Second, children in the TT condition were not permitted to explore the problem space on precriterion trials, so they lacked familiarity with the various problem states and move operators. This familiarity is an important component of transfer (Novick, 1988; Sweller, 1988, 1989). Therefore, any differences between C&C and TT might, at least in part, reflect the importance of problem-space familiarity.

Transfer. After the children met the acquisition criterion, by exhibiting a 7-move (error-free) solution on each of the two consecutive MC analogues, the transfer problem was introduced, with no break in procedure. The transfer problem was a Jh analogue that, like the MC analogues used in acquisition, included five cartoon-type characters. It was called "robots and wrestlers." The robots played the roles of husbands. The two robot/wrestler pairs were each color coded; one pair was green and the other was blue. A third wrestler, whose location was unconstrained, was red.

When the transfer problem was presented, the children were told that the new problem was a little different and the Jh problem constraints were described. The physical materials were then produced, and the children were asked to show how to get everyone across the barrier safely. In transfer, all children received feedback according to the C&C procedure. That is, when an error occurred, the experimenter immediately stopped the child, explained the error, returned the character or characters to the locations they occupied before the error, and requested a new move.

Results and Discussion

We performed several sets of analyses on the acquisition and transfer data. The acquisition analyses included the number of trials to criterion and an evaluation of the amount of time required for each move on the two criterion trials. The transfer analyses included the total number of moves, the number of moves required to advance from each problem state to the next, and the amount of time expended at each problem state. The analogue (first vs. second) presented in acquisition was treated as a within-subject variable, as were data on individual moves within each problem in both acquisition and transfer. We adopted a .05 alpha level as a significance criterion, and contrasts examining main effects were conducted with Fisher's least significant difference (LSD) test. We explored interactions using simple main effect procedures, along with Scheffé contrasts.

Acquisition Data

Trials to criterion. The number of trials to criterion was submitted to a 3 (instructional condition: C&C vs. EXP vs. TT) × 2 (solution information: present vs. absent) × 2 (analogue: first vs. second) analysis of variance. There were significant effects of instructional condition, $F(2, 88) = 3.25$, $MS_e = 2.12$; analogue, $F(1, 88) = 63.26$, $MS_e = 2.04$; and solution information, $F(1, 88) = 5.36$, along with a Solution Information × Analogue interaction, $F(1, 88) = 6.98$. Scheffé contrasts revealed that the interaction reflected a significant difference in favor of the presence of solution information on the first analogue (2.67 vs. 3.67 trials to criterion) but nearly identical scores on the second (1.50 vs. 1.54).

Further analyses revealed that the main effect of instructional condition reflected a significant difference in favor of C&C, as compared with TT (3.94 vs. 5.19 total trials to criterion, respectively). Performance in the EXP condition was intermediate (4.90) and did not differ from either C&C or TT. Most of the difference between the three instructional conditions occurred on the first analogue, on which the range was 2.52 in C&C to 3.58 in EXP (for TT, the value was 3.38); in contrast, the range on the second analogue was only 1.32 in EXP to 1.81 in TT, with an intermediate value of 1.42 in C&C. The Instructional Condition × Analogue interaction did not reach significance, $F(2, 88) = 2.99$, $p = .055$.

Criterion trials. The amount of time expended on each of the 7 moves on the two criterion trials in acquisition was submitted to a 3 (instructional condition: C&C vs. EXP vs. TT) × 2 (solution information: present vs. absent) × 2 (analogue: first vs. second) × 7 (moves on each criterion trial) analysis of variance. Main effects of analogue, $F(1, 88) = 7.16$, $MS_e = 52.17$, and move, $F(6, 528) = 29.40$, $MS_e = 32.88$, were significant. The children averaged 7.7 s per move on their first analogue and 6.6 s per move on their second. There were also significant interactions between instructional condition and move, $F(12, 528) = 1.78$, and between solution information and move, $F(6, 528) = 3.85$. Move data depicting the interactions with training condition and solution information are presented in the upper and lower portions of Table 1, respectively.

Further Scheffé analyses revealed that the effect of training condition was significant only at move number three, on which the children in TT required significantly more time than those in C&C. Although this difference was not predicted, and we have no ready explanation for it, the extra time required by the children in the TT condition may have resulted from their lack of experience with the problem space. Because trials were terminated when errors occurred, children in the TT condition were permitted little opportunity to explore the problem space on precriterion trials, that is, they had little opportunity to become familiar

Table 1
Mean Amount of Time (in Seconds) Required for Each Move on Criterion Trials During Acquisition, as a Function of Instructional Condition and Solution Information Condition

	Move						
Condition	1	2	3	4	5	6	7
Instructional condition							
Explore	11.4	6.5	7.9	6.0	5.7	4.7	3.8
Correct and continue	10.0	6.5	7.4	6.2	8.3	5.5	4.4
Trial terminate	11.5	7.5	11.2	7.9	7.7	5.0	4.1
Solution information							
Absent	11.9	5.9	9.7	5.9	6.3	4.9	4.0
Present	10.1	7.8	7.9	7.6	8.2	5.2	4.3

with the various problem states and move operators before the trial on which they solved each acquisition problem.[4]

In TT, Moves 1 and 3 both required significantly more time than 3 of the remaining 5 moves. In C&C Move 1 was elevated in relation to Move 7, and in EXP the 1st move required significantly more time than 4 others. In general, the last 2 moves took place very fast, always faster than any other move. Scheffé contrasts comparing individual moves at each level of solution information (lower portion of Table 1) failed to reveal any differences between the two conditions on any move.

The pattern of data in each row of Table 1 involves pairs of long and short moves followed by a fast final move. Kotovsky and Fallside (1989) and Kotovsky et al. (1985) obtained an identical pattern of findings in their work with three-disk versions of the Tower of Hanoi problem. They concluded that problem solving is a two-phase process. An initial phase, which corresponds to our precriterion trials, involves problem exploration. During this phase subjects learn enough about the problem to be able to plan pairs of moves. A subsequent phase, which Kotovsky and colleagues call the "final path," results in solution because the subjects plan move sequences that are within their processing limitations. The subjects in their study, like the subjects in our study, exhibited goal–subgoal pairs of moves, followed by a quick final move. That is, subjects learn in the initial phase, through practice in move making, how "to automate or compile the process of planning short (two move) sequences of moves before they . . . [can] plan ahead," which is "a precursor of the final path behavior" (Kotovsky & Fallside, 1989, p. 105).

Transfer Data

Findings from both move and time data in transfer are presented in terms of seven nodes, or locations on solution paths, which are dubbed node units (see Figure 1). A node unit is defined as a unit containing everything that occurs from the time the individual cartoon-type characters are located at node n in the problem space until they are located at node $n + 1$. The correct move, along with errors that resulted in illegal problem states and any other moves that failed to yield progress toward the goal state, are included in each node unit. Stated more precisely, both the correct move and any move that failed to produce a transformation from node n to node $n + 1$ are included in the node unit designated by node n. Only the time the children actually spent pondering their moves and carrying them out was included in the time data. That is, once an error was made, the clock *functionally* stopped while the experimenter explained the error and moved the character or characters to the locations they previously occupied. When the characters were in place, a new move was requested, and the clock began running again.

The move and time data were both submitted to 3 (instructional condition: C&C vs. EXP vs. TT) × 2 (solution information: present vs. absent) × 7 (number of node units) analyses of variance. In the move data, main effects of instructional condition, $F(2, 88) = 3.44$, $MS_e = 0.96$, and

Table 2
Mean Number of Moves Required in Each Node Unit During Transfer for Each Instructional Condition

Instructional condition	Node unit (move) 1	2	3	4	5	6	7
Explore	1.48	1.42	1.26	1.03	1.42	1.19	1.00
Correct and continue	2.52	1.16	1.26	1.00	1.71	1.23	1.00
Trial terminate	2.31	1.16	1.50	1.00	2.34	1.22	1.00

node unit, $F(6, 528) = 18.39$, $MS_e = .90$, were significant, as was the Instructional Condition × Node Unit interaction, $F(12, 528) = 2.63$. In terms of total number of moves in transfer, Fisher contrasts revealed that the children in EXP required significantly fewer moves ($M = 8.81$) than those in the other two instructional conditions and that children in C&C averaged significantly fewer moves ($M = 9.87$) than those in TT ($M = 10.53$).

A similar 3 × 2 × 7 analysis of variance performed on the time data revealed main effects of instructional condition, $F(2, 88) = 3.95$, $MS_e = 798.33$, and node unit, $F(6, 528) = 19.27$, $MS_e = 630.12$, but the interaction between instructional condition and node unit did not reach significance, $F(12, 528) = 1.62$, $p < .10$. The children in EXP required a mean of 81.9 s to complete their transfer problem, those in C&C required 116.9 s, and those in TT required 135.7 s. Fisher contrasts indicated that only TT and EXP differed significantly in terms of total amount of time in transfer. The move and time data for each node unit and instructional condition are presented in Tables 2 and 3, respectively.

Further Scheffé analyses performed on the data in Tables 2 and 3 revealed that on the first node unit, the children in EXP required significantly fewer moves and less time than did those in either the C&C or TT condition, and the latter two did not differ from each other. Thus, when goal attainment was not emphasized, children were better prepared initially to map their base schemas to the nonisomorphic target problem than were children in the other two conditions. We interpret this finding to reflect schema quality, that is, the schemas acquired by children in EXP were of higher quality than those obtained under conditions that emphasized goal attainment.[5]

[4] The children in the TT condition actually averaged about 2.5 moves prior to an error on precriterion trials, so there was some limited exploration of the problem states and move operators.

[5] An anonymous reviewer suggested that children in EXP had more practice than those in C&C during acquisition and that more practice would be expected to lead to a speedup of performance that would be most noticeable on the first move. We have two responses to this suggestion. First, the claim about acquisition may not be accurate. In analysis of the number of trials to criterion, there was a significant main effect of acquisition condition, but in the contrast, C&C differed significantly only from TT whereas EXP was intermediate and did not differ from either C&C or TT. Second, we obtained one very clear finding indicating that amount of practice during acquisition did not have any effect on transfer. The children who received solution information did meet the acquisition criterion in significantly fewer trials than those who did

Table 3
Mean Amount of Time (in Seconds) Required in Each Node Unit During Transfer for Each Instructional Condition

	Node unit (move)						
Instructional condition	1	2	3	4	5	6	7
Explore	23.4	11.1	12.1	7.2	11.9	12.6	3.6
Correct and continue	44.3	13.1	12.9	7.7	22.7	12.1	4.0
Trial terminate	45.1	12.1	17.9	7.0	35.6	13.8	4.3

The importance of familiarity with the various problem states and move operators, which resulted from exploring the problem space on precriterion trials, was demonstrated in subsequent Scheffé analyses. On the fifth node unit, children in the TT condition required significantly more moves than did those in both EXP and C&C and required more time than children in EXP. Thus, the children in EXP and C&C were more readily able to modify procedures in their base schemas to bring them into correspondence with the nonisomorphic target than were children in TT. Thus, increased familiarity with the problem space—the problem states and move operators—during precriterion trials, promotes procedural adaptation during nonisomorphic analogical transfer.[6]

The overall pattern of findings in the transfer data suggests that the quality of the base schema mapped to the target and the processes involved in procedural adaptation may be relatively independent of each other. The difference in favor of EXP, as compared with the other two conditions on the first move, indicates that the effect of decreased emphasis on goal attainment occurs primarily, if not entirely, on the initial mapping process (Tables 2 and 3). The initial mapping process is interpreted to reflect the quality of the base schema that is transferred. The difference in favor of both C&C and EXP, as compared with TT on the fifth move, indicates that problem-space exploration has its effect primarily, if not entirely, on procedural adaptation. The enhanced nonisomorphic transfer that results from greater familiarity with the problem space is attributable to the ease with which procedures in the base schema are adjusted to bring them into correspondence with a target. Thus, when nonisomorphic analogical transfer is an objective, children should be encouraged to thoroughly explore the various problem states and move operators during base acquisition.

[6] Whether similar results would be obtained in semantically rich domains has yet to be addressed. Thus far, cognitive load theory has been applied in the domain of mathematics, which is, like the domain of scheduling problems, semantically impoverished.

Summary and Conclusion

According to cognitive load theory (Sweller, 1988, 1989), two important determinants of analogical transfer are the amount of emphasis on goal attainment and the amount of problem-space exploration. Sweller (1988, 1989) claimed that there is an inverse relationship between the extent to which goal attainment is emphasized and the quality of the schema that is attained during problem solving. The theory also says that there is a direct relationship between successful transfer and familiarity with problem states and move operators that results from problem-space exploration. Thus, cognitive load theory predicts that (relatively) free exploration of the problem space, with little emphasis on goal attainment (as in EXP), should produce a higher quality base schema than constrained exploration that emphasizes goal attainment (as in both TT and C&C). This prediction was confirmed in the present study. Furthermore, because the theory says that transfer is enhanced by familiarity with problem states and move operators, it predicts that when goal attainment is emphasized, exploring the complete problem space on precriterion trials (C&C) should produce better transfer than minimal exploration (as in TT). This prediction was also substantiated by the data.

not receive it. Both the main effect and the interaction with analogue were significant. Thus if amount of practice during acquisition affected transfer, as was suggested, the children who did not receive solution information would be expected to perform better in transfer than those who did. However, there was no hint of any effect involving solution information in the transfer data.

References

Brown, A. L. (1989). Analogical learning and transfer: What develops? In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 369–412). Cambridge, England: Cambridge University Press.

Brown, A. L., Kane, M. J., & Echols, C. H. (1986). Young children's mental models determine analogical transfer across problems with a common goal structure. *Cognitive Development, 1,* 103–121.

Burstein, M. H. (1986). Concept formation by incremental analogical reasoning and debugging. In R. S. Michalski, J. G. Carbonell, & T. M. Mitchell (Eds.), *Machine learning: An artificial intelligence approach* (pp. 351–369). Palo Alto, CA: Tioga.

Cantor, J. H. (1965). Transfer of stimulus pretraining to motor paired-associate and discrimination learning tasks. In L. P. Lipsitt & C. C. Spiker (Eds.), *Advances in child development and behavior* (Vol. 2, pp. 19–58). San Diego, CA: Academic Press.

Carbonell, J. G. (1986). Learning by analogy: Formulating and generalizing plans from past experience. In R. S. Michalski, J. G. Carbonell, & T. M. Mitchell (Eds.), *Machine learning: An artificial intelligence approach* (pp. 137–161). Palo Alto, CA: Tioga.

Duncker, K. (1945). On problem solving. *Psychological Monographs, 58*(5, Whole No. 270).

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 77,* 155–170.

Gentner, D. (1989). The mechanisms of analogical learning. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 199–241). Cambridge, England: Cambridge University Press.

Gholson, B., Dattel, A. R., Morgan, D., & Eymard, L. A. (1989). Problem solving, recall, and mapping relations in isomorphic transfer and nonisomorphic transfer among preschoolers and elementary-school children. *Child Development, 60,* 1172–1187.

Gholson, B., Eymard, L. A., Long, D., Morgan, D., & Leeming, F. C. (1988). Problem solving, recall, isomorphic transfer, and nonisomorphic transfer among third-grade and fourth-grade children. *Cognitive Development, 33,* 37–53.

Gholson, B., Eymard, L. A., Morgan, D., & Kamhi, A. G. (1987). Problem solving, recall, and isomorphic transfer among third-grade and sixth-grade children. *Journal of Experimental Child Psychology, 43,* 227–243.

Gholson, B., Morgan, D., Dattel, A. R., & Pierce, K. A. (1990). The development of analogical problem solving: Strategic processes in schema acquisition and transfer. In D. F. Bjorklund (Ed.), *Children's strategies: Contemporary views of cognitive development* (pp. 269–308). Hillsdale, NJ: Erlbaum.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology, 12,* 306–355.

Gick, M. L., & Holyoak, K. J. (1983). Analogical induction and analogical transfer. *Cognitive Psychology, 15,* 1–38.

Greeno, J. G. (1974). Hobbits and orcs: Acquisition of a sequential concept. *Cognitive Psychology, 6,* 270–292.

Guberman, S. R., & Greenfield, P. M. (1991). Learning and transfer in everyday cognition. *Cognitive Development, 6,* 233–260.

Holyoak, K. J. (1984). Analogical thinking and human intelligence. In R. J. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 2, pp. 199–230). Hillsdale, NJ: Erlbaum.

Holyoak, K. J., & Thagard, P. (1989). Analogical mapping by constraint satisfaction. *Cognitive Science, 13,* 295–355.

Hull, C. L. (1939). The problem of stimulus equivalence in behavior theory. *Psychological Review, 46,* 9–30.

Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence.* New York: Basic Books.

Judd, C. H. (1908). The relation of special training to general intelligence. *Educational Review, 36,* 28–42.

Kotovsky, K., & Fallside, D. (1989). Representation and transfer in problem solving. In D. Klahr & K. Kotovsky (Eds.), *Complex information processing: The impact of Herbert A. Simon* (pp. 69–108). Hillsdale, NJ: Erlbaum.

Kotovsky, K., Hayes, J. R., & Simon, H. A. (1985). Why are some problems hard? Evidence from Tower of Hanoi. *Cognitive Psychology, 17,* 248–294.

Luchins, A. S. (1942). Mechanization in problem-solving. *Psychological Monographs, 54*(6, Whole No. 248).

Novick, L. R. (1988). Analogical transfer, problem similarity, and expertise. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 510–520.

Palmer, S. E. (1989). Levels of description in information-processing theories of analogy. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 332–345). Cambridge, England: Cambridge University Press.

Reed, S. K. (1987). A structure-mapping model for word problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* 124–139.

Reed, S. K., Dempster, A., & Ettinger, M. (1985). The usefulness of analogous solutions for solving algebra word problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 11,* 106–125.

Reed, S. K., Ernst, G. W., & Banerji, R. (1974). The role of analogy in transfer between similar problem states. *Cognitive Psychology, 6,* 436–440.

Reed, S. K., & Johnsen, J. A. (1977). Memory for problem solutions. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 11, pp. 161–201). San Diego, CA: Academic Press.

Rogoff, B., & Gardner, W. (1984). Adult guidance of cognitive development. In B. Rogoff & J. Lave (Eds.), *Everyday cognition: Its development in social context* (pp. 95–116). Cambridge, MA: Harvard University Press.

Ross, B. H. (1984). Remindings and their effects in learning a cognitive skill. *Cognitive Psychology, 16,* 371–416.

Ross, B. H. (1987). This is like that: The use of earlier problems and the separation of similarity effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* 629–639.

Ross, B. H. (1989). Remindings in learning and instruction. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 438–469). Cambridge, England: Cambridge University Press.

Simon, H. A., & Reed, S. K. (1976). Modeling strategy shifts in problem-solving tasks. *Cognitive Psychology, 8,* 86–97.

Sobel, B. (1939). The study of the development of insight in preschool children. *Journal of Genetic Psychology, 55,* 381–388.

Spearman, C. (1923). *The nature of 'intelligence' and the principles of cognition.* New York: Macmillan.

Spence, K. W. (1937). The different response in animals to stimuli varying within a single dimension. *Journal of Experimental Psychology, 31,* 257–271.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science, 12,* 257–285.

Sweller, J. (1989). Cognitive technology: Some procedures for facilitating learning and problem solving in mathematics and science. *Journal of Educational Psychology, 81,* 457–466.

Sweller, J., Chandler, P., Tierney, P., & Cooper, M. (1990). Cognitive load as a factor in the structuring of technical material. *Journal of Experimental Psychology: General, 119,* 176–192.

Thorndike, E. L. (1923). *Educational psychology: The psychology of learning* (Vol. 2). New York: Teachers College, Columbia University.

Thorndike, E. L., & Woodworth, R. S. (1901). The influence of improvement in one mental function upon efficiency of other functions. *Psychological Review, 8,* 247–261.

Titchener, E. B. (1910). *A text-book of psychology.* New York: Macmillan.

(Appendix follows on next page)

Appendix

Setting/Constraint Information for an Analogue of the Missionaries/Cannibals Problem

Ewoks/Pilots

Setting/constraint information: Two brown ewoks and three grey pilots were on one side of a river they needed to cross to get to an air base. They had a small boat, but it would only carry two people at a time. They all knew that there could never be more brown ewoks than grey pilots on either side of the river, because if there were, then the ewoks would hurt the pilots. What they had to figure out was how to get the three grey pilots and the two brown ewoks across the river to the base safely, without any of the pilots getting hurt.

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