Testing Three Theories of Knowledge Transfer

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Abstract

Three theories of knowledge transfer -- analogy, knowledge compilation, and constraint violation -- were tested across three transfer scenarios. Each theory was shown to predict human performance in distinct and identifiable ways on a variety of transfer tasks. Results support the hypothesis that there are *multiple mechanisms* of transfer and that a general theory of transfer must incorporate each mechanism in principled ways.

Introduction

In order to understand human thinking and problem solving in complex and novel situations we need to have a general theory for how people use and adapt their prior knowledge to solve new problems. Aspirations towards such a goal have traditionally been discussed in terms of *transfer*, or how knowledge acquired from one task or situation can be applied to a different situation (Bransford & Schwartz, 1999; Detterman & Sternberg, 1993; Salomon & Perkins, 1989).

Work in cognitive science over the past thirty years has progressed towards this goal by investigating separate strands of transfer phenomena that occur in particular learning and problem solving situations. Although this research strategy has proven successful in developing local, independent explanations of knowledge transfer for particular experimental scenarios (e.g., analogical transfer and transfer appropriate processing), it has done little to bring us closer to a *general theory of transfer*. It is time to begin to weave these separate strands of investigation into a more complete theory that incorporates each strand in principled ways.

It is this charge of theoretical synthesis that motivates the two hypotheses under investigation in the current study. First, it is proposed that there is no single knowledge transfer mechanism, but multiple ones. These mechanisms include (but are not limited to) analogy, knowledge compilation, and error correction. Second, the particular transfer mechanism used depends on both (a) the knowledge actually present and how it is represented, and (b) the processing demands of the transfer task.

Below I summarize some of the prior work on transfer that is relevant to the investigation of these two hypotheses.

Mechanisms of Knowledge Transfer

The first mechanism of interest is *analogical transfer* (Gentner, Holyoak, & Kokinov, 2001). Analogical transfer is composed of three subprocesses: retrieving a prior knowledge structure, creating a mapping between it and the current problem or situation, and then using that mapping to generate new knowledge structures relevant to the application context. The transferred knowledge is typically assumed to be a declarative representation, but it can also include procedural attachments (Chen, 2002).

The empirical evidence for analogical mapping is extensive (Catrambone & Holyoak, 1989; Gentner & Toupin, 1986). However, the evidence also shows that although people are capable of mapping deep relational structures, the retrieval of an analogue is heavily dependent upon matches between the surface features of the current problem and prior problem solving experiences (Catrambone, 2002; Ross & Kilbane, 1997). Therefore, analogy is perhaps a better explanation for near transfer than for far transfer.

The second transfer mechanism of interest is *knowledge compilation* proposed by John R. Anderson and co-workers (Anderson, 1983; Neves & Anderson, 1981). Knowledge compilation was specifically proposed to explain how declarative knowledge is brought to bear on problem solving in the context of the ACT-R theory. This computational mechanism operates through the deliberate and explicit, step-by-step interpretation of a declarative statement that generates new production rules as a side effect. Those rules are then optimized via rule composition and the result is a procedural representation of the content of the declarative knowledge given a specific goal.

The knowledge compilation mechanism can be viewed as a translation device that translates or interprets declarative knowledge (e.g., advice, instructions, and strategies) into a set of procedures and actions that can be used to solve problems. Since knowledge compilation operates on declarative knowledge it can be used in a wide variety of application contexts because the knowledge has yet to be proceduralized, or tied to the goals of a particular problem solving context. This mechanism embodies a tradeoff between applicability and efficiency in that it has wide applicability across many contexts but requires a complicated and lengthy application process to translate the declarative knowledge into a set of actions. There is some empirical support for knowledge compilation but the evidence is not extensive (Anderson, Greeno, Kline, & Neves, 1981; Neves & Anderson, 1981).

The third transfer mechanism of interest is Ohlsson's (1996) *error correction* mechanism. Ohlsson and co-workers (Ohlsson, 1996; Ohlsson & Rees, 1991) have proposed that

the role of declarative knowledge is primarily to help a learner identify and correct his or her own errors. The constraint violation theory has both declarative and procedural components that operate in parallel, and the function of declarative knowledge is to constrain possible problem solutions. When incomplete or faulty procedural knowledge generates undesirable outcomes, these are recognized as violations of those constraints and the responsible rules are revised accordingly.

The power of declarative knowledge is that it can help the learner pinpoint the cause of an error, and transfer is the process by which errors are identified and remedied. This mechanism has wide applicability in that the constraints can be applied to a variety of problems that may require *different* strategies or sequences of actions to produce the correct solution. The constraint violation theory has been shown to generate power law learning curves (Ohlsson, 1996) and to support the design of successful tutoring systems (Mitrovic & Ohlsson, 1999).

In addition to each transfer mechanism using different cognitive processes, each mechanism has also been hypothesized to operate on specific types of prior *knowledge structures*. Analogy uses exemplar knowledge that consists of a declarative representation that may also have procedural attachments (Gentner, 1983). Knowledge compilation uses declarative knowledge such as instructions, advice, or tactical knowledge (Anderson, 1983). Error correction uses declarative knowledge of the constraints for a particular problem domain (Ohlsson, 1996).

In summary, researchers have proposed multiple alternative transfer processes including analogy, knowledge compilation, and error correction. Each mechanism has been associated with a particular kind of transfer scenario that specifies the conditions necessary for transfer (i.e., type of prior knowledge and application context). The purpose of the current study is to test the predictions of each transfer theory, and ask whether we can predict what transfer mechanism will be triggered for a given set of transfer scenarios.

The Present Study

In order to test these theories I implemented a between-groups training study in which subjects were given one of three training scenarios (exemplar, tactics, or constraints) and then were tested on a common set of problem solving tasks.

Each training scenario was designed to facilitate the construction of one of the three of the aforementioned knowledge structures associated with each transfer mechanism (i.e., exemplars for analogy, tactics for knowledge compilation, and constraints for error correction). In the exemplar training condition participants solve problems similar to those used in the transfer phase. In the tactical training condition participants learn instructional tactics for solving the transfer problems. In the constraints training condition participants learn the constraints associated with the problem solving task domain.

The transfer task is Thurstone's *letter extrapolation task* (Thurstone & Thurstone, 1941). In this task subjects are given a sequence of letters containing a pattern and their task is to find the pattern and continue it. Here is a simple example, A B M C D M . . . the correct continuation is E F M G H M. An important aspect of these problems for the current purposes is that prior declarative and procedural knowledge can make them easier to solve.

Although letter extrapolation is an invented task, it has several elements in common with many real world tasks including: a prior knowledge base (e.g., the alphabet), conceptual content (e.g., the pattern), materials to study (e.g., tactics), and generativity (e.g., one has to generate a sequence of coordinated actions).

Three different extrapolation problems were used in the transfer phase. Each problem was constructed with different properties or affordances, to elicit quantitative (accuracy, solution time, self-corrected errors) and qualitative (solution type) differences in performance from each training group.

The first transfer problem was designed to have a similar surface and deep pattern structure as that used in the exemplar training problems. This problem can also be solved by applying either tactical or constraint knowledge. The second transfer problem is open-ended and depending on how the given sequence is interpreted, different solution types are expected. This problem shares the same deep structure as the exemplar problems. However, the surface similar characteristics are misaligned and suggest a different interpretation. If the given sequence is interpreted as similar to the *surface sequence* one solution is expected. If it is interpreted as a *deep analogy* a second solution is expected. Tactical knowledge can also be used to solve this problem and biases one towards the second solution. Constraint knowledge can be applied as well and does not provide an a-priori bias towards any one of the correct solutions. The third transfer problem has neither surface nor deep structure similarity to the exemplar problems. The tactics are also not directly applicable. However, the constraints can be applied to find a unique solution.

In addition to comparing task performance across training groups, each training group was compared to a *no-training* control group for a measure of transfer relative to baseline performance.

Predictions

Exemplar Training. If participants in this training condition use exemplar knowledge and analogy to solve the first transfer problem they are expected to show high accuracy and fast solution times with few error-correcting behaviors as compared to the no-training group. They should show fast solution times for this problem because there is both surface and deep similarity to the training exemplars (i.e., fast memory access). They should show few error-correcting behaviors because they can transfer both declarative and procedural knowledge from the exemplars. For transfer problem 2 participants are expected to show high accuracy with slower solution times and few self-corrected errors. In

addition, they should show a bias for the surface similar problem solution. For transfer problem 3 they should show similar performance to no-training participants.

Tactical Training. If participants in this training condition use tactical knowledge and knowledge compilation to solve the first two transfer problems they should show high accuracy but similar solution times and error-correcting behaviors to that of the no-training group. In addition, for transfer problem 2 they should show a bias for the tactics relevant solution. For transfer problem 3 they should show similar performance to that of the no-training participants.

Constraints Training. If participants use constraint knowledge and error correction to solve all three transfer problems they should show high accuracy, similar solution times, and many error-correcting behaviors compared to the no-training group. In addition, they should show more variability in solution types for transfer problem 2.

Methods

Participants

One hundred and twenty-five undergraduate students from the University of Illinois at Chicago's subject pool participated in return for partial course credit.

Materials

Training Materials. The training materials for the *exemplar group* consisted of four sequence extrapolation problem isomorphs. Each problem was presented on a separate sheet of paper. All four training problems had the same deep pattern structure as each other and the first two transfer problems, but each was instantiated with different surface features. Below are two examples:

Exemplar 1: L M Z M L Y M N X . . .
Exemplar 2: E F S F E R F G Q . . .

The training materials for the *tactics group* consisted of a general tutorial, a tactic summary sheet, and several blank recall sheets. The tutorial (10 pages) provided instruction on specific kinds of pattern relations including: *forward*, *mirror-flip*, *backward*, *repeat*, and *identity*. Each pattern relation was defined and multiple examples were given. The tactics summary sheet consisted of one pattern continuing tactic and four pattern finding tactics including: (1) look for mirror flips or periods to break apart the pattern, (2) repeated letters may signal a mirror-flip order of symbols, group repeat, or period marker, (3) letters that are far apart in the alphabet may signal a mirror-flip alphabet, (4) letters close together may signal backward or forward relations. The tactics could be used to solve the first two transfer problems.

The training materials for the *constraints group* consisted of a constraints tutorial, constraint summary sheet, blank recall sheets, and letter string violation worksheet. The tutorial (5 pages) provided instruction on four letter pattern constraints: (1) all *completed* letter strings must be divisible into six groups of letters, (2) the number of letters in each similar group must be the same, (3) each letter group must be derived from either the immediately preceding letter group or the letter group two back, (4) letter operations must be repeated. The string violation worksheet provided a series of completed letter strings in which the participants' task was to identify constraint violations.

Test Materials. The test tasks were three letter extrapolation problems. See Table 1 for each transfer problem and its solution(s). The first extrapolation problem had a periodicity of three letters. It was superficially similar to the exemplar training problems and shared the same deep pattern structure. This problem could also be solved by applying either tactics or constraint knowledge. Subjects were asked to continue the solution to six positions.

The second extrapolation problem also had a periodicity of three letters. However, the correct continuation was ambiguous and was dependent on how the subject interpreted or "parsed" the given sequence. There are two primary solutions depending on the interpretation of the given sequence. If the letters are parsed into cross period relations of *forward-1* and *backward-1* comparable to surface similar relations used in the exemplar problems, one solution type will be derived (see Table 1, solution 1). However, if the given string is instead parsed as cross period relations of *mirror-flip-alphabet* and *backward-1* relations as suggested by a deep analogy or pattern finding tactic 3, a different solution will be derived. Subjects were asked to continue the solution to nine positions. In addition, there were four other possible correct solutions.

The third problem had a periodicity of two letters and had neither surface nor deep structure similarity to the exemplar problems. In addition, there was no pattern finding tactic that directly applied to this problem. However, a unique solution could be derived by constraint application. The pattern consists of pairs of letters incrementally increasing through the alphabet, each pair skipping an additional letter as the pattern progresses.

Table 1. Transfer problems and their solutions.

Problem Type	Given letter sequence & the correct extrapolation
Transfer 1	
	Given: R S F S R E S T D T S C . . .
	Solution → T U B U T A
Transfer 2	
	Given: B C P X Y O C D N . . .
	Solution 1 → Y Z M D E L Z A K
	Solution 2 → W X M D E L V W K
Transfer 3	
	Given: B A C B E D H G . . .
	Solution → L K Q P

Transfer problems were presented on a Macintosh computer with a 17'' color monitor, standard keyboard and mouse. Problems were presented in black 30 pt font in the center of the screen. The transfer portion of the experiment was designed and presented using PsyScope software.

Design

A between-subjects design was used with subjects randomly assigned to one of four training conditions: *exemplar training* (n = 31), *tactic training* (n = 31), *constraint training* (n = 33), and *no-training* (n = 30). Participants were tested individually. The procedure consisted of a training phase and a transfer phase.

Procedure

Training procedure for the exemplar group. Participants were first given general instructions for solving extrapolation problems. Next they were given three minutes to solve the first training problem. After three minutes participants received feedback on each position of their solution. If they extrapolated any position of the solution incorrectly they were given another instance of the same problem and three minutes to solve it. This cycle continued until the problem was solved correctly or the participant made four attempts to solve that problem. After the first problem this same procedure was continued for the remaining three training problems.

Training procedure for the tactics group. Participants first read the general tutorial. Next they memorized a summary sheet of the tactics for three minutes. Then they were given a simple unrelated distractor task to solve (e.g., three arithmetic problems). Participants were then asked to recall and write down all of the tactics. The experimenter assessed memory performance for recall of each tactic. If the subject omitted or incorrectly recalled any of the tactics they were given the tactic summary sheet to study again for another two minutes. After the second memorization phase they were given another distractor task followed by recall. This cycle was continued until the subject recalled all five tactics. After correct recall the subjects were asked to explain each tactic to the experimenter. If the subject gave an incorrect explanation the experimenter provided the correct explanation.

Training procedure for the constraints group. Participants first read the constraints tutorial. Next they memorized a summary sheet of the four constraints for three minutes. They were then given an unrelated distractor task to solve. Participants were then asked to recall the constraints and were given feedback on their recall performance. If they omitted or incorrectly recalled any of the constraints they were given the constraint summary sheet to memorize for another two minutes. After the second memorization phase they were given another distractor task followed by a blank recall sheet. This cycle continued until participants recalled all four constraints. After correct recall of the constraints subjects were asked to explain each constraint to the experimenter. If the subject gave an incorrect explanation the experimenter provided the correct explanation. Participants were then given the string violation worksheet.

Training procedure for the no-training group. Participants in this condition did not receive any training and served as a comparison condition of baseline performance on the transfer tasks.

Test procedure for all training groups. Subjects were seated at the computer and were told that they were to solve three extrapolation test problems. They were instructed that the given string of each transfer problem would be presented on the left side of the computer screen and that there would be an empty box for each letter position they were to extrapolate and fill in. Subjects were informed that they could re-enter new letters in any given position as many times as they would like. Subjects were told to click the mouse on the "Finished" field after all solution positions were filled and they were finished solving the problem. After the initial instructions participants were presented with each problem one at a time and given six minutes to solve each one.

Results and Discussion

Training Performance

Subjects in all three training groups were trained to criterion. The criterion measure for the exemplar group was solving at least two of the training problems completely correct. The criterion measure for the tactical and constraints groups was complete recall and correct explanation of the tactics and constraints respectively. Three subjects in the constraints training condition and one subject in both the exemplar and tactical training conditions did not pass the criterion. These subjects were excluded from further analysis leaving thirty subjects (n = 30) in each training group.

The training criterion provides evidence that each subject learned the target knowledge during the training phase (i.e., subjects in the exemplar group could solve training problems and subjects in the tactical and constraints group could recall declarative knowledge from memory). Next, I examine whether these subjects could transfer this knowledge to the problem solving tasks.

Transfer Performance

The three measures of central interest for the transfer phase were participants' accuracy scores and behavioral profiles across the three transfer problems, as well as the type of solution used to solve problem 2.

Accuracy Performance. To assess overall transfer performance participants' accuracy scores were examined for each training group. The *accuracy score* was the proportion of solution positions correctly extrapolated for a given transfer problem. The mean accuracy scores and standard deviations for each training group on the transfer problems are presented in Table 2.

Table 2. Mean proportion of solution positions correctly extrapolated for each transfer problem.

Training	Transfer1	Transfer2	Transfer3
Exemplar	.93* (.19)	.80 (.26)	.21 (.43)
Tactics	.78* (.32)	.71 (.32)	.22 (.37)
Constraints	.70* (.34)	.74 (.33)	.23 (.41)
No-training	.40 (.36)	.69 (.38)	.29 (.43)

A 4 (training) X 3 (problem type) mixed-analysis of variance (ANOVA) revealed a significant interaction of training by problem type, F (6, 232) = 6.46, $p < .05$. Follow-up comparisons showed that the interaction was best explained by the large advantage of the training groups over the no-training group on transfer problem 1, F (6, 232) = 43.14, $p < .05$, but not on problems 2 and 3, F (6, 232) = .76, *ns* and F (6, 232) = 1.41, *ns* respectively.

As predicted, all three training groups showed high accuracy in solving the first two transfer problems. Problem 1 in particular shows that the knowledge generated from each training condition facilitated transfer resulting in significantly higher accuracy performance than the no-training group. Although the constraints training group showed high accuracy on the first two transfer problems they did not show high accuracy scores on the final problem. One potential explanation for this lack of predicted transfer is that solving the first two transfer problems provided participants with partial exemplar knowledge that interfered with constraint application (this issue is further discussed in the conclusion).

Behavioral Profile. In order to assess whether a given participant used a particular transfer mechanism an ideal behavioral performance profile was created for each transfer mechanism. The use of a particular transfer mechanism can be evidenced by a constellation of scores across a set of dependent variables, what I term the *behavioral signature*.

The dependent variables used in this assessment included the accuracy score, the solution time, the number of self-corrected errors, and the checking time. The *solution time* was the total time in seconds to solve the problem. The *self-corrected error score* was the total number of times a subject re-entered a new letter into a given solution position that changed a previous response. The *checking time* was the amount of time in seconds between a subject's last extrapolation response and clicking on the finished button. This was presumably an indirect measure of error-checking behavior.

Using this set of dependent measures an ideal behavioral signature was created for each transfer mechanism (see Table 3). The qualitative indices (e.g., fast vs. slow) for a given variable are in comparison to the average no-training baseline performance.

Table 3. Ideal behavioral signatures for each transfer mechanism.

Behavior	**Transfer Mechanism**		
	Analogy	Knowledge Compilation	Error-Correction
High Accuracy	√	√	√
Fast Solution	√		
Error Checking			√

The ideal behavioral signature for analogical transfer was a high overall accuracy, a fast solution time on problem 1, and few error correcting behaviors. The ideal behavioral signature for knowledge compilation was a high overall accuracy, similar solution times and error correcting behaviors. The behavioral signature for error-correction was high accuracy, similar solution times, and a high number of error correcting behaviors.

Each subject's performance was examined as to whether it fit with a particular behavioral signature. For a subject's accuracy performance to be classified as *high* he or she had to have an overall accuracy score higher than the average (collapsed across problem) of the no-training group. For a subject's solution time to be classified as *fast* it had to be at least 1 standard deviation faster than the average solution time of the no-training group. Subjects were classified as having high error checking behavior if their performance met one of two criteria. The participant must have either scored 1 standard deviation above the average no-training group on both of the error measures (i.e., many self-corrected errors and long checking time), or have scored 2 standard deviations above on a single error measure. The number of subjects classified under each behavioral signature is shown in Table 4.

Table 4. Number of subjects classified under each behavioral signature.

Training Condition	**Behavioral Signature**			
	Analogy	Knowledge Compilation	Error-Correction	Other
Exemplar	19*	9	0	2
Tactics	2	16*	6	6
Constraints	3	7	13*	7

Chi-square tests showed that the training groups differed in the number of subjects classified for a given behavioral signature, χ^2 (6, N = 90) = 43.10, $p < .05$. Follow-up tests showed that more subjects trained on exemplars used analogy than those trained on tactics or constraints, χ^2 (2, N = 30) = 31.02, $p < .05$, more subjects trained on tactics used knowledge compilation than those trained on exemplars or constraints, χ^2 (2, N = 30) = 6.49, $p < .05$, and more subjects trained constraints used error-correction than those trained on exemplars or tactics, χ^2 (2, N = 30) = 16.94, $p < .05$.

In summary, the majority of subjects in a particular transfer condition showed the expected pattern of behavioral results as predicted by the three theories of transfer. This provides evidence that these three mechanisms are triggered under particular learning and transfer task conditions.

Solution Type. In addition to accuracy performance and behavioral profiles, further support for transfer can be assessed via the types of solutions participants used on problem 2. The number of subjects to use a given solution type is provided in Table 5.

Table 5. The number of subjects from each training group to use a given solution type.

Training Condition	Correct Solution Type		
	Solution 1	Solution 2	Others
Exemplar	19*	1	1
Tactics	5	12*	4
Constraints	12	0	4
No-training	9	0	9

Chi-square tests showed that the training groups significantly differed in the number of subjects to use a particular solution type, χ^2 (6, N = 77) = 41.68, $p < .05$. Of particular interest is that more exemplar training subjects used solution 1 than those given other forms of training, χ^2 (3, N = 77) = 20.80, $p < .05$, and that more tactics training subjects used solution 2 than subjects from the other groups, χ^2 (3, N = 77) = 29.70, $p < .05$.

In sum, these results provide further evidence that participants used training knowledge to solve the transfer problems. Subjects given exemplar training showed a preference for the surface similar solution and the tactics group showed a preference for the tactics relevant solution.

Conclusion

The results from this study provide support for the hypothesis that there are multiple mechanisms of transfer that are distinct and identifiable. Subjects in three separate transfer scenarios exhibited behavioral patterns of performance consistent with those predicted by three theories of knowledge transfer.

Several review articles have pointed out that the transfer literature exhibits a mixture of both positive and negative results (Bransford & Shwartz, 1999; Salomon & Perkins, 1989). While some studies have failed to find large transfer effects where we intuitively expect them, others have found transfer effects under particular types of study and test conditions. The complexity of the empirical results suggests that transfer is a heterogeneous phenomenon. Greater clarity might result if we assume that *different transfer processes are triggered in different types of transfer scenarios*. Results from the current study suggest that to understand transfer one must take a multifaceted approach and examine several interrelated aspects of the transfer scenario, not just one or two variables from a single theoretical perspective. Progress towards a general theory of transfer requires the synthesis and integration across current lines of research.

Future work should examine the interaction of these transfer mechanisms and investigate whether people are capable of *adaptively shifting between mechanisms* depending on their prior knowledge and the processing demands of the transfer task.

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