

An Investigation into Adaptive Shifting in Knowledge Transfer

Timothy J. Nokes (tnokes@uiuc.edu)

Beckman Institute
University of Illinois at Urbana-Champaign
Urbana, IL 61801 U.S.A.

Abstract

Participants were trained on three knowledge types -- exemplars, tactics, and constraints -- and then thought aloud while solving a series of transfer problems. Results show that participants shift between the transfer mechanisms of analogy, knowledge compilation, and constraint violation depending on their prior knowledge and the characteristics of the transfer tasks.

Introduction

A central goal of cognitive science is to develop a general theory of *transfer* to explain how people use and apply their prior knowledge to solve new problems. To construct such a theory scientists need to identify and articulate the cognitive processes involved in the access, retrieval, and application of prior knowledge to new situations. Previous work has taken a 'divide and conquer' approach to attaining this goal. Researchers have pursued separate lines of inquiry by investigating the cognitive processes of transfer for particular learning and problem solving scenarios. This work has led to the development of several specialized theories of transfer including analogical transfer (Gentner, 1983), knowledge compilation (Anderson, 1983), constraint violation (Ohlsson, 1996), and transfer appropriate processing (Morris, Bransford, & Franks, 1977), among others.

Although this research has contributed to our understanding of particular kinds of transfer, it has done little to address how these transfer processes interact and relate to one another. A complementary research strategy is *theory unification*. If our ultimate goal is to develop a general theory of transfer we need to articulate how the local theories 'fit together' within a larger cognitive framework (Newell, 1990). If each theory postulates a particular kind of transfer mechanism, then those mechanisms must eventually be realized within one and the same cognitive system.

The purpose of the current work is to take the first steps towards this goal by synthesizing across previous theories of transfer in an effort to elucidate how a subgroup of transfer mechanisms relate to and interact with one another. Building upon previous work, I investigate whether people are capable of *dynamic shifting between multiple mechanisms of transfer* depending on their prior knowledge and the characteristics of the transfer tasks.

Theories of Transfer

The three theories of transfer investigated in the current work are analogy, knowledge compilation, and constraint

violation. These theories are of particular interest because each proposes a computationally well-defined transfer mechanism that operates on different types of knowledge structures. In this section I briefly review each theory and describe their scope of application.

Analogical transfer consists of three main parts: retrieving a prior analogue from memory, aligning and mapping the analogue to a target, and then drawing an inference from that mapping to the target scenario (Gentner, Holyoak, & Kokinov, 2001). Analogical transfer operates on exemplar knowledge that is typically assumed to be a declarative representation, but it can also include procedural attachments (Chen, 2002). Prior empirical work has shown that analogical retrieval is facilitated by surface feature similarity to the target scenario (Catrambone, 2002) whereas alignment and mapping is facilitated by structural similarity (Gentner, Ratterman, & Forbus, 1993). These results suggest that analogy is triggered by tasks that are similar on the surface and share the same relational structure.

Knowledge compilation is a method by which prior declarative knowledge (instructions, tactics, or facts) can be used to solve novel problems and perform new tasks. It can be viewed as a translation device that translates prior declarative knowledge into a set of procedures and actions for performing a particular task or solving a specific problem. Knowledge compilation operates through the deliberate and explicit, step-by-step interpretation of a declarative statement that generates new procedures (production rules) as a side effect. Those rules are later optimized via rule composition, and the result is a procedural representation of the declarative knowledge given a particular goal (Anderson, 1983; Taatgen & Anderson, 2002). Previous work has shown that declarative knowledge can apply to a variety of different tasks but is costly in terms of the time required to proceduralize that knowledge to the current problem context (Nokes & Ohlsson, in press).

Constraint violation is a three-part process that involves a generate-evaluate-revise transfer cycle in which a learner uses prior knowledge of the domain constraints to evaluate and correct her or his task performance (Ohlsson, 1996). According to the theory the learner generates an initial solution based on general problem solving strategies and then evaluates that solution with respect to her or his prior knowledge of the constraints. If a constraint is violated, the learner attempts to revise the faulty procedure(s) and generate a new solution. This process is repeated until a correct solution is found that satisfies all of the constraints. Transfer is the process by which the learner uses her or his

prior constraint knowledge to identify and remedy the errors generated while performing new tasks. The theory postulates that constraint knowledge applies to a wide variety of tasks but is costly in that it requires multiple iterations of *error correction* to obtain a correct solution.

A large amount of work has been dedicated to these independent lines of transfer research. Some recent attempts have also been made to synthesize these approaches into a more unified theory of transfer. For instance, in a prior study designed to systematically manipulate individuals' prior knowledge to examine each mechanism across a variety of transfer tasks, Nokes (2004) found that the mechanism triggered depended on the learner's prior knowledge and the processing demands of the transfer task. In this study, participants were first trained in one of the three knowledge types associated with each of the transfer mechanisms (i.e., exemplars for analogy, tactics for knowledge compilation, and constraints for constraint violation). Then each group solved a common set of transfer problems. Participants in each training group exhibited behavioral patterns of performance that were consistent with those predicted by each of the transfer theories.

Although the Nokes (2004) study provided strong evidence that distinct multiple mechanisms exist, how these mechanisms interact remains uncertain. In order to test the interaction of multiple mechanisms, the person under examination needs to have all three types of prior knowledge. The central question addressed in the current work is whether people trained on all three types of knowledge are capable of *adaptive shifting between transfer mechanisms* depending on the characteristics of the transfer problems. Of particular interest is whether people will use the *optimal mechanism of transfer* for a given transfer problem. The optimal transfer mechanism is defined as the mechanism that can be applied to the given transfer task to produce a correct solution with the least amount of cognitive effort. I predict that a person will use analogy if the transfer task has surface and deep structure similarity to one's prior exemplar knowledge (even when knowledge compilation and constraint violation could also be used to solve the problem). If the transfer task does not trigger analogical retrieval (i.e., it has different surface features), it is predicted that a person will then use knowledge compilation of tactics to solve the problem (even when constraint violation could also be used to derive a correct solution). Finally, if the transfer task triggers neither exemplar knowledge or tactics application (i.e., no surface similarity exists and the tactics are not relevant) people are expected to use constraint violation to solve the problem.

Experiment

To test these hypotheses I implemented a within-subjects design where each participant was trained on all three types of knowledge structures and then solved three transfer problems. The training and transfer materials were the same as those used in Nokes (2004). The training materials consisted of exemplar problems, tactical problem solving

instructions, and instruction in the domain constraints. The transfer tasks were three sequence extrapolation problems (Thurstone & Thurstone, 1941).

The three transfer problems were each designed with specific task characteristics to trigger an optimal transfer mechanism. The first transfer problem had a similar surface and deep structure to the exemplar problems. The tactics and constraints could also be applied to solve this problem. The second transfer problem had an open-ended structure and there were multiple plausible solutions depending on the interpretation of the given pattern. The problem had misaligned surface and deep structure as compared to the exemplar problems. If the surface features were used one solution was expected whereas if the deep structure was used a second solution was expected. The tactics could also be applied to this problem and were biased to this second solution. In addition, the constraints could be used to solve the problem and did not provide an a priori bias to any one of the possible solutions. The third transfer problem had neither surface nor structural similarity to the exemplar problems. The tactics were also not directly applicable. However, the constraints could be used to derive a correct solution.

In addition a no-training control group was tested on the three transfer problems to provide a measure of baseline performance.

Predictions

Specific predictions were derived for each transfer problem.

Transfer Problem 1. Participants are expected to use analogy to solve this problem because the surface and deep structure are similar to the exemplar problem. Participants should show a preference for analogy over tactics and knowledge compilation because analogical transfer should require less adaptation of the prior knowledge structure. In particular, if participants use analogy they will have knowledge of both the declarative pattern as well as the procedures for extrapolating that pattern. In contrast, if participants use tactics they must figure out the pattern as well as the action implications for extrapolating that pattern, two tasks that require substantial cognitive processing. Similarly, the participants are not expected to use constraint violation because the generate-evaluate-revise process requires multiple iterations and substantial processing time. It is predicted that the training participants will show high accuracy and fast solution times as compared to the no-training group, reflecting transfer of both declarative and procedural knowledge. In addition, training participants' are expected to make explicit statements of analogy while solving the problem.

Transfer Problem 2. Participants are expected to use tactics and knowledge compilation to solve this problem because the surface and deep structure features are *misaligned* with those from the exemplar problems. Without proper alignment between the surface and structural elements analogical retrieval may not occur, and mapping would require substantial adaptation of the prior knowledge structure. Participants should prefer tactics and knowledge compilation to constraint violation because the tactics are

directly applicable to the features of the problem and offer a *more direct route* to pattern identification. In contrast, the constraint violation process requires several iterations of general problem solving, constraint checking, and error correction -- a time intensive process that can only indirectly lead to a correct solution. It is predicted that participants will show high accuracy and long solution times, reflecting knowledge compilation processes. Participants are also expected to show a bias for using the tactics relevant solution. In addition, participants' verbal protocols should exhibit application of the tactics.

Transfer Problem 3. Participants are expected to use constraint violation to solve this problem because it does not have surface or structural similarity to the exemplar problems, nor do any of the tactics directly apply. It is possible however, that participants may initially try these strategies to solve this problem, although it is predicted that they will run into an impasse that will motivate a switch to constraint violation. It is expected that participants will show high accuracy and long solution times, reflecting multiple iterations of constraint violation. In addition, participants' verbal protocols are expected to exhibit statements of constraint application and error correction.

Methods

Participants

Forty-eight 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 consisted of three parts: exemplars, tactics, and constraints (see Table 1 for examples of each). Exemplar materials consisted of four exemplar problem isomorphs. Each problem had similar surface features and the same deep structure as one another. The tactics materials included a 10 page tactics tutorial, a tactics summary sheet, and several blank recall sheets. The constraints training materials consisted of a 5 page constraints tutorial, constraint summary sheet, blank recall sheet, and letter string violation worksheet.

Table 1. Example material from each section of training.

Section	Examples
Exemplars	(1) L M Z M L Y M N X . . . (2) E F S F E R F G Q . . .
Tactics	(1) <i>look for mirror flips or periods to break apart the pattern</i> (2) <i>letters far apart in the alphabet may signal a mirror-flip alphabet relation</i>
Constraints	(1) <i>all completed letter strings must be divisible into six groups of letters</i> (2) <i>the number of letters in each similar group must be the same</i>

The presentation of the training materials was counterbalanced, producing 6 versions of training. There was also a final review section that consisted of the summary materials from each of the training sections.

Transfer Materials. The transfer tasks were three extrapolations problems. See Table 2 for each transfer problem and its solution(s). The first extrapolation problem had a periodicity of three letters. It had similar surface and deep pattern structure to the exemplar problems. The tactics and constraints knowledge could also be applied to solve this problem. Subjects were asked to continue the solution to six positions.

The second extrapolation problem also had a periodicity of three letters. However, there were six plausible solutions dependent on how the subject interpreted the given sequence. There were two primary solutions of interest. If the letters are parsed into cross period relations of *forward-1* and *backward-1*, similar to the exemplar surface features, solution 1 will be derived. Alternatively, if the given string is parsed as cross period relations of *mirror-flip-alphabet* and *backward-1*, similar to the deep relations of the exemplar and tactic number 2, solution 2 will be derived. Subjects were asked to continue the solution to nine positions.

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 violation. The pattern consists of pairs of letters incrementally increasing through the alphabet, each pair skipping an additional letter as the pattern progresses.

Table 2. Test problems and their solutions.

Problem Type	Given letter sequence & the correct extrapolation
Transfer 1:	R S F S R E S T D T S C . . . Solution → T U B U T A
Transfer 2:	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:	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 (Cohen, MacWhinney, Flatt, & Provost, 1993).

Design

A within-subjects design was used with participants randomly assigned to one of the six training orders ($n = 38$). In addition, a no-training control group was used as a

comparison of baseline performance ($n = 10$). All participants received the same set of transfer problems in one of two transfer orders. Half of the participants received *order 1* (problems: 1-2-3) and other half received *order 2* (problems: 3-2-1). Participants were trained and tested individually.

Procedure

Training Phase. Participants were given initial instructions and an overview of the experiment. The training phase was divided into three sections: exemplars, tactics, and constraints. Participants were given a brief break between any of the sections if they so desired.

Exemplar Section. Participants were given initial instructions and three minutes to solve the first training problem. After three minutes they received feedback on each position of their solution. If the participant 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 practice 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 exemplars.

Tactics Section. Participants first read the tactics tutorial. Next they were given three minutes to memorize a summary sheet of the five tactics. They were then asked to perform a simple distractor task (i.e., three arithmetic problems) after which they were asked to recall and write down all of the tactics. The experimenter assessed their recall performance for each tactic. If they omitted or incorrectly recalled any of the tactics, they were given an additional two minutes to study the tactics summary sheet. After the second memorization phase they were given another distractor task followed by a blank recall sheet. This cycle was continued until the subject recalled all five tactics. After subjects correctly recalled all of the tactics they were asked to explain each tactic to the experimenter. If a subject gave an incorrect explanation the experimenter provided the correct one.

Constraints Section. Participants first read the constraints tutorial. Next they were given three minutes to memorize a summary sheet of the four constraints. They were then asked to solve an unrelated distractor task. Next participants were 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 two additional minutes to study the constraints summary sheet. After the second memorization phase they were given another distractor task followed by a blank recall sheet. This cycle continued until they recalled all four constraints. After correctly recalling the constraints subjects were asked to explain each constraint to the experimenter. If a subject gave an incorrect explanation the experimenter provided the correct one. Participants were then given the string violation worksheet. After completing the worksheet the experimenter gave them feedback on their performance.

Training Review. After completing all three sections there was a one-minute break followed by a three-minute review of the summary materials from each section.

Transfer Phase. Participants were instructed to think aloud while they solved letter extrapolation problems on the computer. They were told that the given string of each letter problem would be presented on the left side of the computer screen and that there would be an empty box for each letter they were to fill in. To fill in a box they were told to click the mouse on the box and press the appropriate letter. The subjects were told that they could fill in the solution positions in any order they chose. After all solution positions were filled and they had finished solving the problem subjects were told to click the mouse on the “Finished” field. Participants were informed that the training could help them solve the problems. They were presented with each extrapolation problem one at a time and were given 8 minutes to solve each one.

Results and Discussion

Training Performance

Participants were trained to criterion for each section of the learning phase. The criterion measure for the exemplar section was solving at least two of the training problems correctly. The criterion measure for the tactics and constraints sections was complete recall of the tactics and constraints respectively. All but two subjects passed the criteria. These subjects were excluded from further analysis leaving thirty-six ($n = 36$) subjects in the training group.

The training criterion provides evidence that each subject acquired all three of the knowledge structures from the training phase. In the next section I examine whether these subjects could transfer this knowledge to the problem solving tasks.

Transfer Performance

Multiple measures of problem solving performance were used to assess transfer of training including accuracy, solution type, solution times, and subjects’ verbal protocols. Initial analyses revealed no effect or interactions for *training* or *test order* and all subsequent analyses collapsed across these groups.

Accuracy Performance. To assess overall transfer performance participants’ accuracy scores were examined for each group. The *accuracy score* was the proportion of solution positions correctly extrapolated for a given transfer problem. Each groups mean accuracy scores and standard errors for each transfer problem are presented in Table 3.

Table 3. Mean proportion of solution positions correctly extrapolated for each transfer problem.

Condition	Transfer1	Transfer2	Transfer3
Training	.86 (.05)	.85 (.03)	.22 (.06)
No-training	.63 (.10)	.84 (.06)	0

A 2 (training) x 3 (problem) mixed analysis of variance (ANOVA) revealed a main effect for transfer problem, $F(2, 88) = 61.27, p < .05$, indicating that overall accuracy differed across the transfer problems. There was also a main effect of training, $F(1, 44) = 7.04, p < .05$, indicating that the training group had an overall higher accuracy than the no-training group. In addition, there was no interaction of problem by training, $F(2, 88) = 1.58, ns$. Follow-up comparisons for the effect of transfer problem revealed that overall performance was much better on problems 1 and 2 than on problem 3, $F(1, 45) = 99.45, p < .05$, and $F(1, 45) = 123.25, p < .05$, respectively.

These results show that the knowledge acquired from training facilitated problem solving performance. In particular the training participants showed mean accuracy advantages over the control group on transfer problems 1 and 3. Although the interaction was not significant the training and no-training groups showed similar accuracy scores on transfer problem 2. One plausible explanation for the control group's high mean accuracy is that problem 2 had multiple possible solutions and therefore participants were more likely to generate a correct solution. This hypothesis is further explored in the next section where I examine the types of solution used to solve this problem. In addition, the fact that both the training and no-training groups performed worse on transfer problem 3 suggests that this problem was particularly difficult to solve.

Solution Type for Transfer Problem 2. In addition to accuracy performance, further support for knowledge transfer can be assessed via the types of solutions participants used on problem 2. The proportion of subjects to use each solution type is presented in Table 4.

Table 4. The proportion of subjects to use each solution type.

Condition	Solution Type			Unclassified
	Solution 1	Solution 2	Other Correct	
Training	19%	53*%	17%	11%
No-training	40%	0%	40%	20%

Chi-square tests show that the groups significantly differed in the number of subjects to use a particular solution type, $\chi^2(3, N = 46) = 9.10, p < .05$. Of particular interest is that more training subjects used solution 2 than those given no training, $\chi^2(1, N = 46) = 8.99, p < .01$. In contrast, there was no difference between training and no-training groups to use solution 1, $\chi^2(1, N = 46) = 1.81, ns$.

These results show that although the training and no-training groups had similar mean accuracy scores they used different kinds of solutions to solve the problem. As predicted, subjects given training showed a preference for the tactics relevant solution. These results are also consistent with those obtained in the Nokes (2004) study that showed when participants were trained on tactics alone they showed a bias to use solution 2 whereas participants trained on exemplars alone showed a bias to use solution 1.

Solution Time. The solution times were used to assess the amount of cognitive processing required to solve the transfer problems. Because participants were given 8 minutes to solve each problem their solution times varied between 0 and 480 seconds. The training and no-training group's mean solution times and standard errors on each transfer problem are presented in Table 5.

Table 5. Mean solution times and standard errors for each transfer problem.

Condition	Transfer1	Transfer2	Transfer3
Training	121* (15)	221 (19)	299 (26)
No-training	223 (53)	204 (34)	312 (33)

A 2 (training) x 3 (problem) mixed ANOVA was conducted to investigate the effect of training on solution times across transfer problems. The analysis revealed a main effect for transfer problem, $F(2, 88) = 12.12, p < .05$, indicating that overall solution times differed across the transfer problems. There was no main effect for training, $F(1, 44) = 1.05, ns$. However, there was a marginally significant interaction of training by problem, $F(2, 88) = 2.47, p = .09$. Follow-up analysis for the interaction shows an effect of training for problem 1, $F(1, 44) = 6.45, p < .05$, but not problems 2 and 3, $F(1, 44) = .17, ns$ and $F(1, 44) = .06, ns$ respectively.

The training participants had much faster solution times than the no-training group on transfer problem 1 but not on problems 2 and 3. This result suggests that the training participants used analogy and transferred procedural knowledge from exemplar training to transfer problem 1.

Verbal Protocols. A summary measure for the number of subjects to have protocol evidence implicating the use of each transfer mechanism was assessed across the three transfer problems. To assess whether or not each participant used a particular mechanism, the number of statements they generated for each mechanism was assessed (i.e., the statements implicating use of analogy, tactics, or constraints application). If a participant's score for a particular transfer mechanism was above the average score of the no-training group she or he was classified as showing evidence for using that mechanism. Comparing training participants' scores to the average of the no-training group separates the effects from training from those expected from normal problem solving. The number of subjects classified as showing evidence for each transfer mechanism across the problems is presented in Table 6.

Table 6. The number of training participants to show protocol evidence for each mechanism.

Transfer Problem	Transfer Strategy		
	Analogy	Tactics	Constraint
Transfer 1	4*	15	7
Transfer 2	1	21*	13
Transfer 3	0	14	17*

The results show that the number of subjects to have protocol evidence for the various transfer mechanisms shifted across the transfer problems. In particular, there was a relative shift for more participants to use the predicted mechanism across the three transfer problems. These results also indicate that there was substantial individual differences in strategy use with some subjects using multiple mechanisms and others using non-optimal transfer mechanisms for a given transfer problem. In addition, although participants' short solution times on problem 1 suggested that they used analogy and exemplar knowledge to solve this problem very few of these subjects made explicit analogies. One plausible explanation for the lack of protocol evidence is that analogical transfer in this scenario may have been primarily an implicit process (as suggested by the procedural transfer). This interpretation is consistent with other recent accounts of analogy as fast mapping between a source and target knowledge structure (Day & Gentner, 2003).

Summary. Participants showed high accuracy, fast solution times, and protocol evidence for using verbal analogies as well as tactics and some constraint application on problem 1. These results provide converging evidence that participants primarily used analogical transfer of exemplar procedures to solve this problem coupled with some tactics and constraint application. On problem 2 participants showed high accuracy, long solution times, a bias towards generating the tactics relevant solution, and protocol evidence for tactics and constraint application suggesting they primarily used tactics and knowledge compilation to solve this problem coupled with some constraint application. On transfer problem 3 participants showed moderate accuracy, long solution times, and protocol evidence for constraints and tactics application suggesting that participants primarily used constraint violation to solve this problem coupled with tactics application.

Conclusion

The results from this experiment provide converging evidence for the hypothesis that *people shift between multiple mechanisms of transfer depending on their prior knowledge and characteristics of the transfer tasks*. In particular, the results demonstrate that participants: (1) show a relative shift to using analogy and exemplar knowledge to solve the transfer tasks that have similar surface and deep structure matches to their exemplar knowledge, (2) show a relative shift to using tactics and knowledge compilation when their exemplar knowledge is no longer accessible (even though there may be deep structural similarity), and (3) show a relative shift to using constraints violation when they encounter a problem that does not prompt exemplar knowledge and tactics are no longer relevant. In addition, substantial individual differences were observed in participants' verbal protocols suggesting that some participants used multiple mechanisms for a given problem.

This work takes the first steps towards elucidating how these mechanisms interact, and in determining the conditions

under which each mechanism is triggered. Science progresses through both theory specialization as well as attempts unify those theories within a common framework. Future work should focus on developing a formal model that incorporates each transfer mechanism into one and the same cognitive architecture.

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