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ABSTRACT

The primary goal of this discussion is to summarize research on the role of expertise in accounting for individual differences in analogical problem solving among college students. The discussion also relates expertise differences to current theorizing in the developmental literature that concerns analogical reasoning in children. Contents focus on the domain of math story problems. Results of three experiments involving undergraduate students that elucidate the role of domain expertise in promoting analogical transfer are reported. It was hypothesized that when a source problem is strucurally analogous to a target problem but shares few, if any, surface features with that problem, spontaneous positive transfer should be higher for experts than for novices. This hypothesis and its converse were tested in two experiments. Results suggested that expertise is important in determining the success of the retrieval component of analogical transfer and that novices have greater difficulty than experts in ignoring misleading surface similarity. A third experiment examined the importance of expertise for executing the post-retrieval processes of mapping and procedure adaptation. It is concluded that age differences in analogical reasoning among children seem to parallel expertise differences among adults. (RH)

The Role of Expertise in Analogical Problem Solving

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It has often been suggested that young children are inferior to older children and adults in the sophistication of their analogical reasoning mechanism. Indeed, whether measured by performance on the types of proportional analogies found on mental tests or by performance on story problem analogies, the ability to reason analogically historically has been thought not to emerge until the formal operational period of development. More recently, however, evidence for analogical competence among preschoolers has cast doubt on the stage view of analogical development. The large individual differences among college students, who years earlier supposedly entered the formal operational stage, also are inconsistent with the traditional view of development.

The primary goal of my talk is to summarize the role of expertise in accounting for individual differences in analogical problem solving among college students. This discussion will focus on the domain of math story problems, because that is where relevant research has been conducted. A second goal is to relate the expertise differences to current theorizing in the developmental literature concerning analogical reasoning in children. Recently, Brown (1989), Goswami (1991), and Vosniadou (1989) have all been arguing against the stage view of the development of analogical reasoning ability. Instead, they argue that age differences in performance on analogical reasoning tasks, when they occur, are due to younger children's deficient knowledge concerning the causal relations about which they are asked to reason. In other words, what develops is not the ability to engage in analogical reasoning, but the conceptual system upon which such reasoning must operate.

Although studies of analogical problem solving in children have focussed on non-mathematical domains, there seems to be a reasonably close mapping between developmental differences and expertise differences observed for math problem solving. For example, transfer differences within a particular age group can profitably be understand by reference to expertise differences. In addition, when young children are tested in domains for which they have considerable knowledge concerning the underlying causal relations, their performance resembles that of adult experts; and when they are tested in domains about which they are naive, their performance resembles that of adult novices.

I will report the results of three experiments using college undergraduates that elucidate the role of domain expertise in promoting analogical transfer. Links between the findings for expertise and results from the developmental literature will be discussed where appropriate.

Before discussing the role of expertise in analogical transfer, it is important to consider briefly the nature of that skill. Solving a target problem by analogy to a source problem requires the execution of several component processes. First, a relevant source problem must be retrieved from memory. Successful retrieval will depend on having an appropriate representation of both problems, because features of the target representation will be used as retrieval cues to search memory for a relevant problem encountered previously. Once a potential source problem has been retrieved, the solver must compute a mapping between the source and target problems. Assuming that the solution-relevant features of the two problems correspond, the solver can then adapt the source solution for use with the target problem. Thus, analogical problem solving requires the successful execution of three component processes: retrieval, mapping, and adaptation. In addition, as already suggested, it will be influenced by the nature of the representations constructed for the source and target problems.

Previous work has shown that experts and novices differ in their representations of problems: Novices' representations are based primarily on surface features, such as the specific objects and terms mentioned in the problems. In contrast, experts' representations focus more on structural features, such as the relations among the problem elements, particularly the causal relations that are directly tied to satisfying the goals of the problem. Because the features included in one's representation of the target problem determine the retrieval cues available for finding potentially-analogous problems in memory, the expertise differences in problem representation should have predictable consequences for the performance of experts and novices in a transfer experiment. In particular, when the source problem is structurally analogous to the target problem but shares few if any surface features with that problem, spontaneous positive transfer should be higher for experts than for novices. I will refer to such a source problem as a remote analog. Conversely, when the source and target problems are not structurally analogous but have many surface features in common, spontaneous negative transfer should be higher for novices than for experts. I will refer to the structurally-dissimilar but superficially-similar source as a distractor problem.

The results of two experiments provide support for these hypotheses (Novick, 1988), thereby suggesting the importance of expertise in determining the success of the retrieval component of analogical transfer. Experiment 1 tested the positive transfer hypothesis using a 2x2 design in which two levels of expertise were crossed with presence or absence of the remote analog. Because the source and target problems were complex arithmetic story problems, performance on the math section of the SAT served as the measure of expertise. The experts and novices had average math SAT scores of 729 and 603, respectively. The procedure learned for the source problem, and transferrable to the target problem, was based on finding multiples of the lowest common multiple of several numbers. I will refer to it as the LCM procedure. Baseline use of the LCM procedure in the control condition, when the remote analog was absent, was comparable in the two expertise groups, with 6% of the subjects in each group inventing that procedure on their own. As predicted, experts were much more likely to show spontaneous positive transfer than were novices, with 56% versus 6% of the subjects in the two expertise groups, respectively, using the LCM procedure to solve the target problem in the source-present condition.

A considerable amount of research in the developmental literature can be interpreted as yielding similar results. Brown, Kane, and Echols (1986) asked preschoolers to recall the source story before solving the target problem. If children's recalls are taken to reflect their representations of the source problem, then recalls that include the problem's goal structure reflect more expert encoding of the problem than do recalls that focus on the story's details. Mirroring my findings, the transfer rates for children who produced goal-structure versus story-detail recalls were approximately 80% and 20%, respectively. Chen and Daehler (1989) found similar results for the 6-year-olds in their study. The transfer rate was higher for children whose encodings of the source problems included an abstract description of the solution principle. Gholson, Morgan, and Dattel (1990) reported similar results for preschoolers through sixth-graders solving variations of the missionaries and cannibals river-crossing problem. At each age level, what predicted the strength of transfer was the quality of understanding of the underlying structure of the source problems. Finally, Goswami and Brown (1989) found that the age difference in performance on proportional analogies for 3, 4, and 6-year-olds mimicked the age difference in understanding of the causal relations underlying the analogies.

Now let me turn to my second experiment, which tested the negative transfer prediction. In that experiment, subjects received both the remote analog and the distractor problem. Earlier work had shown that baseline use of the procedure taught for the distractor problem, which is inappropriate for solving the target problem, is about 12% for both expertise groups. The experts and novices had average math SAT scores of 731 and 560, respectively. As predicted, novices were much more likely to show spontaneous negative transfer than were experts, with 73% versus 46% of the subjects in the two expertise groups, respectively, attempting to use the incorrect procedure from the distractor problem to solve the target problem. Moreover, if we consider only those subjects who showed negative transfer, the experts were less persistent in trying to adapt the incorrect procedure for use with the target problem: Only 9% of them made more than one attempt to use the incorrect procedure, compared to 39% of the novices.

Although I am not aware of any studies in the developmental literature in which children have been presented with a situation similar to the one I used with college students, two sets of researchers have recently reported some relevant data. In one condition of Chen and Daehler's (1989) recent experiment, which I mentioned earlier, 6-year-olds either induced or were taught the common solution principle for two inappropriate source problems. Thus, these subjects had an expert representation of those problems. As in my study, a moderate amount of negative transfer was observed: 46% of the children tried to apply the ineffective procedure to the target problem, compared to only 17% of children using that procedure in the control condition. Chen and Daehler also reported results from a group of children who received the inappropriate source problems but were not given the common solution principle. It is difficult to relate the results for that condition to my results, however, because the source and target problems did not have surface features in common, and subjects' representations for the source problems were not reported.

The results of my second experiment also could be interpreted as indicating that when appropriate structural information is present in a transfer situation, novices have greater difficulty than experts in ignoring misleading surface similarity. Under this interpretation, a link might be made between my study and one conducted by Gentner and Toupin (1986). Those researchers found that when relevant structural information was provided (in what they called their "systematic" condition), 4-6 year olds but not 8-10 year olds were adversely affected by a cross-mapping manipulation that provided misleading surface similarity information. Because understanding the causal structure of the stories required understanding sophisticated emotions and motivations such as jealousy and greed, it is possible that the younger children were akin to novices in terms of their knowledge bases. This link between the results of the two studies must be considered tentative, because Gentner and Toupin did not test the children's knowledge of the causal relations used in the stories.

The results of the studies reviewed so far suggest the importance of expertise in determining the success of the retrieval component of analogical transfer. Recently, Keith Holyoak and I have examined the importance of expertise for executing the post-retrieval processes of mapping and procedure adaptation (Novick & Holyoak, 1991). All subjects received the remote analog and were told to use its solution procedure to solve each of two similar target problems. In other words, the retrieval process was performed for subjects. In addition, half of the subjects were told the mapping of the important concepts between each target problem and the source problem: for example, the band members are like plants and the rows and columns of band members are like kinds of plants. An earlier experiment found that providing this information was no more effective in promoting successful transfer than was simply telling subjects to use the source problem to help solve the target problem. The remaining subjects were told the mapping of the numbers between each target problem and the source problem: for example, the 5 in the band problem is like the 6 in the garden problem. Rather than preselecting subjects on the basis of math SAT scores, that information was collected after the experiment was completed, and the contribution of expertise to transfer performance was assessed using correlation and regression analyses. The scores ranged from 410 to 780, with a mean of 625.

Mapping the numbers between the source and target problems was important for transfer, as transfer success was greater after the number-mapping hint than after the concept-mapping hint, with means of 2.30 and 1.35, respectively, on a 4-point scale. Nevertheless, the ability to figure out the numerical mapping on one's own did not seem to be related to expertise. After solving the second target problem, subjects who received the concept-mapping hint were asked to generate the numerical mapping between that problem and the source problem. On average, subjects correctly identified 90% of the numerical correspondences, and success on this task was not reliably correlated with math SAT scores. I am currently conducting a more well controlled study to better determine whether math expertise is related to success at mapping elements of math story problems. Some theories of analogical mapping, such as that of Holyoak and Thagard (1989), would predict similarly high mapping performance over a wide range of expertise.

In contrast to the seeming ease of mapping, the process of adapting the LCM procedure for use with the target problems was quite difficult, as evidenced by the errors subjects made in attempting to apply the procedure to the target problem. Averaged across the data from this experiment and a similar experiment, 67% of the subjects attempted adaptation. Of these subjects, 54% made one or more errors. Moreover, of the subjects whose adaptation attempts eventually were successful, 24% initially made errors. Also in contrast to the results for the mapping process, there was a highly reliable positive correlation between expertise and successful adaptation. In a multiple regression analysis, both the type of mapping hint (that is, concept hint versus number hint) and math expertise were highly reliable predictors of transfer success.

Unfortunately, there is very little data concerning execution of the adaptation process in either adults or children. My new mapping study, mentioned earlier, will provide an opportunity to replicate the relation between expertise and adaptation success. Gholson and his colleagues are beginning to study the adaptation process in children using variations of the missionaries and cannibals river-crossing problem. Gholson, Morgan, and Dattel (1990) speculate that with increasing expertise in a domain may come more facile strategies for executing the adaptation process of analogicai transfer.

In an attempt to better understand the relation between expertise and adaptation success, Keith Holyoak and I correlated math SAT scores with the occurrence of each of a variety of adaptation errors that were coded from the written solution protocols. These analyses indicated that although math expertise predicts overall success of the adaptation process, it does not predict the occurrence of specific adaptation errors. We concluded that expert subjects' presumably better mastery of the four constituent operators of the LCM procedure might enable them to hold all of the relevant procedural knowledge in working memory while performing the integration necessary for adaptation. In other words, the benefit conferred by greater expertise may be greater facility at coordinating adaptation of a multi-step procedure.

This facility at coordination can be considered a metacognitive ability. It seems reasonable that deficits in the ability to monitor one's progress toward solution would decrease the likelihood of successful transfer, but would not necessarily predict specific types of errors. For example, low monitoring might simply decrease somewhat the probability that each required adaptation is executed successfully. This explanation fits well with the general belief that experts in a domain have greater metacognitive competence than do novices.

Brown (1989) has argued recently that the age differences in analogical transfer that remain after knowledge levels have been equated might be attributable to greater metacognitive competence among the older children. If this parallel between expertise differences and age differences is found to hold up, it will strengthen the general analogy between young children and novices. At this point, however, I can only echo Brown's conclusion that the contribution of metacognitive skills to analogical transfer would seem to be a fruitful area for future research.

In sum, where relevant data have been collected, age differences in analogical reasoning among children seem to parallel expertise differences among adults. Where relevant data do not exist in one domain or the other, current theorizing would predict parallel results.

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