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Abstract

Some theories of analogical mapping predict that finding mappings based on relations between objects requires greater working-memory capacity than finding mappings based on attributes of individual objects. It follows that the ability to make relational mappings will be impaired by any manipulation that constricts available working memory capacity. This prediction was tested in two experiments using a mapping task that required finding correspondences between pairs of pictures in which a critical object was "cross-mapped" (attribute similarity supporting one mapping, relational similarity another). Working memory was constricted in Experiment 1 by requiring participants to maintain a digit load while performing the mapping, and in Experiment 2 by inducing anxiety using a speeded subtraction task administered prior to the analogy task. Both manipulations caused participants to produce fewer relational responses and more attribute responses. The findings support the postulated links among working memory, anxiety, and the ability to perform complex analogical mapping.

Introduction

A basic characteristic of mental representations is that they have a hierarchical form, in which simpler elements are systematically integrated to create more complex structures. Hierarchical representations appear to be used in object and scene perception, in language production and comprehension, and in text comprehension and memory. There is evidence that similarity judgments depend on hierarchical representations based on relations between elements (Medin, Goldstone & Gentner, 1993). Formally, relational representations have a predicate-argument structure, in which one or more elements are bound to distinct roles. Gentner (1983) proposed a taxonomy of representational complexity ranging from attributes (one-place predicates, such as tall (Abe)); to first-order relations (multi-place predicates that take objects as role fillers, such as taller-than (Abe, Bill)); to higher-order relations (multi-place predicates in which at least one role filler is itself a proposition, such as cause (taller-than (Abe, Bill), jealous-of (Bill, Abe))). For the purposes of the present paper it will suffice to distinguish representations based on attributes of individual objects from representations based on relations (either first-order or higher-order) among multiple objects.

Both attributes and relations can provide a basis for finding analogical correspondences, or mappings, between situations. In some cases, correspondences based on information at different levels of complexity may conflict, creating ambiguous cross mappings between elements of the two analogs (e.g., Gentner & Toupin, 1986; Ross, 1987). For example, Markman and Gentner (1993) showed college students pairs of pictures, such as a man bringing groceries from a truck and giving them to a woman, who is thanking him, and a different woman taking food from a bowl and giving it to a squirrel. Participants were asked to indicate which object in the second picture corresponded to the woman in the first picture. Based on attribute mapping, the woman in the first picture would map to the woman in the second picture; but based on relations, the woman in the first picture would map to the squirrel in the second picture because each is a recipient of the food.

Markman and Genter found that different participants gave different responses to such cross-mapped objects, some giving the attribute-based response and some giving the relation-based response. Manipulations that encouraged participants to build an integrated representation of the relations among the objects and of higher-order relations between relations increased the proportion of relational responses. In particular, if participants were asked to match not just one object in the first picture (the woman), but three (the woman, man, and groceries) to objects in the second picture, they were more likely to map the woman to the squirrel on the basis of their similar relational roles than were participants who mapped the woman alone. Active mapping of multiple objects seems to encourage people to process relations, which in turn changes the apparent correspondences between individual objects.

Although people are clearly capable of finding mappings based on multiple levels of representational complexity, there is reason to expect that relational mappings impose greater demands on working memory than do attribute mappings (Halford, 1993; Halford, Wilson & Phillips, 1998; see Baddeley, 1986, 1992, for a discussion of the components of human working memory). For example, mapping the woman in the first picture to the woman in the second picture can be done by focusing on only one object in each picture; whereas mapping the woman to the squirrel requires representing multiple objects and relations in each picture in order to recognize the correspondences between the objects filling matching roles in a system of relations. Some computational models of analogical mapping, such as the STAR model of Halford et al. (1994) and the LISA model of Hummel and Holyoak (1997), postulate inherent limitations on the complexity of possible mappings due to working-memory limits. Such models lead to the general prediction that any manipulation that reduces available working-memory capacity will make it more difficult for reasoners to compute relational mappings, and hence increase the proportion of less-complex attribute mappings in situations in which the mapping is ambiguous.

The results of a number of behavioral studies suggest there is a close relationship between the ability to process multiple relations and the functioning of working memory. Many of these studies have involved the performance of reasoning tasks concurrent with the execution of secondary tasks designed to place demands upon working-memory systems. In a study using a dual-task paradigm to investigate the information processing demands of relational reasoning, Maybery, Bain, and Halford (1986) required subjects to respond to a probe at different stages in the solution of three-term series (transitive inference) problems. Maybery et al. found that reaction times to the probe were longest during the phases of the problems in which premise integration took place: during the presentation of the second premise and during the presentation of the proposition to be verified. Their results were interpreted as indicating that the process of relational premise integration involved greater information-processing requirements than the sequential processing of individual relations, in that premise integration requires multiple relations to be simultaneously active in working memory.

It follows that the ability to make relational mappings will be impaired by any manipulation that constricts available working memory capacity. This prediction was tested in two experiments using a mapping task based on the Markman and Gentner (1993) materials. College students were asked to find correspondences between pairs of pictures in which a critical object was cross-mapped. Working memory was constricted in Experiment 1 by requiring participants to maintain a digit load while performing the mapping, and in Experiment 2 by inducing anxiety using a speeded subtraction task administered prior to the analogy task. The anxiety manipulation was based on Eysenck's (1979, 1985; Eysenck & Calvo, 1992) working-memory restriction theory, according to which the cognitive component of anxiety involves self-preoccupation and concern over performance, which preempt part of the processing and storage resources of the working-memory system. Processes that require working-memory resources will be impaired when anxiety causes the available system capacity to be exceeded, whereas lower-level processes will be relatively unaffected by anxiety. (See Eysenck & Calvo, 1992, for a review of studies that support the working-memory restriction theory of anxiety over alternative accounts.)

Experiment 1

College students performed an analogical mapping task with possible cross-mappings while simultaneously performing a secondary task that would tax working memory. The central prediction was that imposing a load on working memory would selectively impair the generation of correspondences based on relations, so that relational mappings would be made less frequently whereas attribute mappings would be made more frequently.

Method

Participants. Forty-five undergraduate students from the University of California, Los Angeles (UCLA) served in the experiment.

Materials and apparatus. Macintosh microcomputers running the SuperLab software package were used to present the stimuli. The stimuli consisted of the eight pairs of pictures used by Markman and Gentner (1993), as well as eight different 7-digit number strings. Each of the pictures showed a visual scene with three or more objects. One of these objects could be cross-mapped; that is, it could be judged as corresponding to one object on the basis of physical attributes, but to a different object on the basis of the role it plays in a system of relations.

Design and procedure. A 2 x 2 between-subjects design was used, with each participant randomly assigned to one of four conditions. The variables manipulated were the number of objects in each picture for which participants were prompted to identify correspondences (one or three) and the presence or absence of a phonological working memory load. Half of the participants were assigned to the 1-map condition and half were assigned to the 3-map condition. Orthogonally, half of the participants in each group were required to hold digit strings in working memory concurrent with performance of the mapping task, and half were not.

Each participant sat individually at a computer with an experimenter. Written instructions were displayed on the computer screen, explaining the procedure and the tasks to be performed. For each pair of pictures, the experimenter would point to a set of objects in the first picture. The participant's task was to identify the objects in the second picture that corresponded to each of those indicated by the experimenter. In the 1-map condition, participants were prompted to identify the object in the bottom picture corresponding to one object (the cross-mapped one) in the top picture. In the 3-map condition, participants were simultaneously asked to identify the objects in the bottom picture corresponding to three objects in the top picture. The first object to be mapped in the 3-map condition was the same cross-mapped object that was that was the single object to be mapped in the 1-map condition.

The phonological working-memory load required participants to hold a random 7-digit number string in memory while performing the mapping task. After pointing to their answer(s) to the mapping task, participants in this condition were asked to recall the 7-digit number. The experimenter recorded the participants' responses to the mapping questions, as well as their digit recall. All participants viewed each of the eight picture-pairs once, and all participants viewed the pairs in the same order.

Results and Discussion

The dependent variable was the proportion of correspondences identified by the participants on the basis of relational similarity. The results are depicted in Figure 1. The effects of number of mapping questions (1-map versus 3-map) and presence or absence of a working-memory on the percentage of relational mappings were analyzed using a 2 X 2 between-subjects analysis of variance. The analysis revealed a main effect of mapping instruction, such that the mean percentage of relational responses was significantly higher in the 3-map condition than in the 1-map condition (M = 60% versus 39%), $F(1, 41) = 6.64$, MSE = .0778, $p < .05$. A main effect of working-memory load was also observed, such that the mean percentage of relational responses was significantly lower when a digit string had to be maintained than when there was no memory load, (M = 35% versus 64%), $F(1, 41) = 12.48$, MSE = .0778, $p < .01$. There was no significant interaction between number of mapping questions and memory load, $F(1, 41) < 1$.

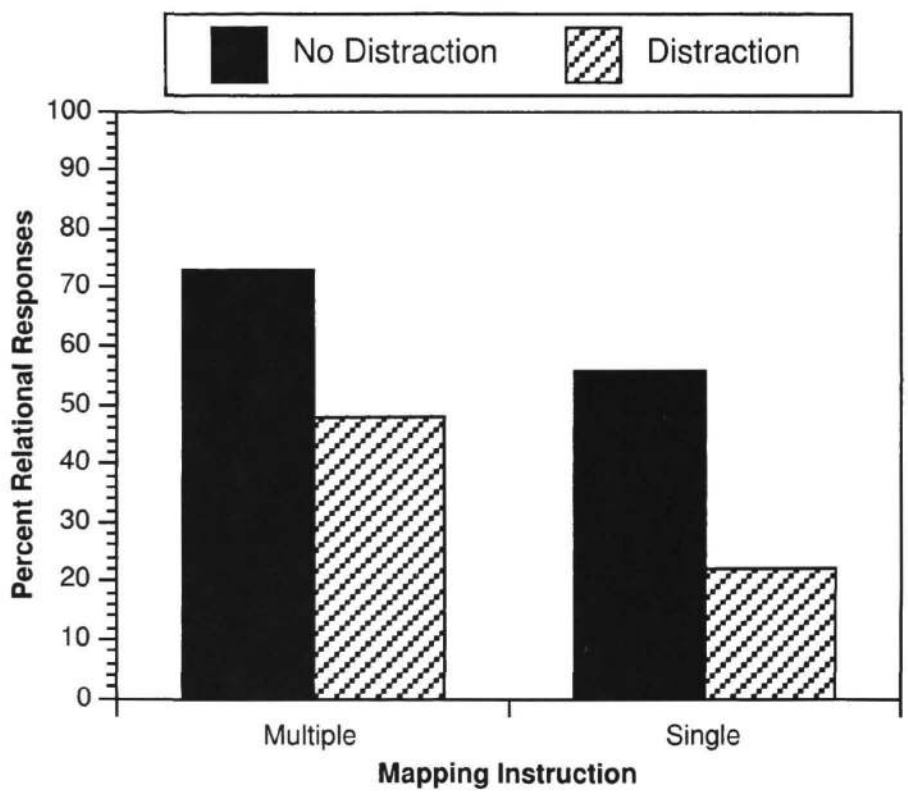

Figure 1. Percent relational responses given by subjects as a function of workinng memory load and mapping instruction.

Experiment 2

When Eysenck's (1979) working-memory restriction theory of anxiety is coupled with theories of analogy that specify links between working-memory capacity and the complexity of analogical mappings (Halford et al., 1994; Hummel & Holyoak, 1997), it follows that when objects are cross-mapped, an increase in state anxiety will yield a decrease in relational mappings and a concomitant increase in attribute mappings. Experiment 2 was designed to test this prediction.

Method

Participants. The participants were 22 UCLA undergraduates.

Materials. The stimuli were identical to those used in Experiment 1, with the addition of two extra pairs of pictures that were created by the third author using a computer graphics program.

Design and procedure. Participants were tested individually. They were assigned randomly in equal numbers to one of two conditions, the Anxious and Non-anxious groups. For participants in the Anxious condition, anxiety was induced by the introduction of a stressful task at the beginning of the experimental session. Specifically, their first task was to perform a serial subtraction task aloud. The participant was instructed to count aloud backwards, beginning at 1000 in increments of 13. One experimenter corrected any mistakes, while a second experimenter indicated to the participant at a pre-determined time that their counting speed was too slow. The participant was instructed to stop when 45 seconds had elapsed. The experimenter then informed the participant that they would be asked to repeat the counting task at the end of the experiment. This serial subtraction task has been used successfully to induce anxiety in previous studies (Sgoutas-Emch et al., 1994; White & Yee, 1997).

In the Non-anxious condition, the participant was asked to count aloud (forward) beginning at 1 for 45 seconds. Participants were told that they were not being evaluated in any way and to count at a pace that felt relaxed for them.

For the remainder of the experiment, the procedure was identical for both groups, and was equivalent to the 1-map condition used in Experiment 1 and in Markman and Gentner (1983). Each pair of pictures appeared for a fixed duration before the participant was queried for their response. Specifically, the picture-pair was programmed to appear for 15 seconds, after which the screen flashed, at which point the experimenter pointed to the pre-determined cross-mapped object in the top picture. This procedure was used to avoid participants giving premature responses while allowing ample time to process the pictures relationally. If more than approximately 4 seconds elapsed before the participant responded, the experimenter prompted the participant for an immediate answer. After the participant indicated the object of their choice, the experimenter recorded the response on an answer sheet. The above procedure was repeated for each of the ten picture analogies.

Table 1: Mean STAI Scores and Percentage of Relational Mappings in Experiment 2

Condition	STAI[a]	Percent Relational Mappings
Anxious	43.0	45 .4
	(8.1)	(23.4)
Non-anxious	32.7	68 .2
	(8.1)	(20.9)

Note. Values enclosed in parentheses represent standard deviations. [a]State score of the Spielberger State Trait Anxiety Inventory (Spielberger et al., 1970).

After the analogical reasoning task, participants completed the state form of the State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch & Lushene, 1970), and then were debriefed.

Results and Discussion

Mean STAI and mapping scores (percentage of relational mappings) for the Anxious and Non-anxious conditions of Experiment 1 are reported in Table 1. The anxiety manipulation was successful, as the mean STAI state-anxiety rating for the Anxious group was significantly higher than that for the Non-anxious group, $F(1,20) = 8.90$, MSE = 65.21, $p = .008$ (means of 43.0 and 32.7, respectively; maximum = 80). As predicted by the hypothesis that anxiety will restrict working memory, which is required for relational mappings, participants in the Anxious condition produced a significantly lower percentage of relational mappings than did those in the Anxious condition, $F(1,20) = 5.78$, MSE = 4.92, $p = .026$ (means of 45% and 68%, respectively). In both conditions, the remaining responses were primarily attribute mappings (51% and 24%, respectively, for the Anxious and Non-anxious conditions); only about 8% of responses in each condition were neither the relational nor the attribute mapping. Thus the impact of anxiety was not to produce random errors, but rather to systematically shift the dominant basis for mapping from the more complex relational level to the simpler attribute level.

General Discussion

We found that people who were asked to determine correspondences between visual scenes, while either concurrently holding information in phonological working memory or under the burden of high anxiety caused by a preceding difficult task, identified fewer correspondences on the basis of relational similarity than those who were not hindered by working-memory loads. Importantly, people who mapped under working-memory loads did not simply make unsystematic errors; rather, the basis for their mapping responses shifted from relations to attributes. Our results indicate that the process of structural alignment places greater demands upon working memory than does the process of matching attributes.

The finding that the process of structural alignment involves increased working memory demands is consistent with neuropsychological evidence that the capacity to integrate relations is lost as a consequence of damage to prefrontal cortex that reduces working-memory capacity (Waltz et al., 1999). We hypothesize that the representation of a system of relations, which specifies relations between relations, places demands upon working memory because it requires the explicit representation and binding of multiple relations (Robin & Holyoak, 1995). Our findings suggest that one of the primary consequences of factors that reduce available working-memory resources in learning environments is an impairment in the identification and learning of relations.

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