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Investigating the Effect of Analogical Processing on Mental Representations

A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of
Philosophy in Psychology

by

Michael Scott Vendetti

2013

ABSTRACT OF THE DISSERTATION

Investigating the Effect of Analogical Processing on Mental Representations

by

Michael Scott Vendetti

Doctor of Philosophy in Psychology

University of California, Los Angeles, 2013

Professor Keith J. Holyoak, Co-Chair

Professor Barbara J. Knowlton, Co-Chair

My thesis focuses broadly on how memory may be influenced by performing analogical comparisons. I am interested in understanding how mapping objects between two domains based on a shared relational structure may influence how we encode and retrieve that information. When we use analogies to gain knowledge in our everyday thinking, we often make comparisons between two domains that highlights shared, relational roles, potentially at the expense of other information. Research on memory has indicated that how we encode information depends on the knowledge structures we have about a given scenario, such that events and objects that are relevant to our pre-existing knowledge representations are likely to be easily integrated, potentially at the cost of losing exact features of that information. Other research has shown that items in memory that compete during retrieval may influence each other's memory strength through an inhibitory mechanism. Across the two studies described here, I examined whether these memory phenomena are triggered by analogical mapping. I found that analogical mapping influenced memory, specific to those items that fit into a common relational category. I also discovered that memories for items sharing a relational structure could inhibit information that did not fit into that relational structure, suggesting that how we reason can influence how we recall and represent information.

The dissertation of Michael Scott Vendetti is approved.

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University of California, Los Angeles

2013

Dedication

To my parents, who encouraged me to follow my passions, and showed me that anything worth having in life requires a lot of effort.

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Chapter 1: General Introduction to Reasoning, Memory and Abstraction

Role-based Relational Reasoning

The ability to compare structured mental representations is fundamental to complex human cognition (Penn, Holyoak & Povinelli 2008; Robin & Holyoak, 1995). Role-based relational reasoning occurs when comparisons are made based on the relations among elements in a particular domain, rather than just on the specific overlap of features between domains (Holyoak, 2012). Being able to focus on common, underlying relational structures instead of possible featural similarities between two domains in order to generate inferences between them is heavily dependent on one's ability to maintain and manipulate representations in working memory, as well as to compare higher-order relationships. This type of reasoning has been shown to rely heavily on availability of resources in working memory (Waltz et al., 1999), fluid intelligence (Gray & Thompson, 2004), and is predictive of academic success and proficiency in the workplace (Gottfredson, 1997, 2002).

One type of role-based relational reasoning that will be a major topic of this thesis is analogical reasoning, in which comparisons are made between a more familiar source domain (typically retrieved from memory) and a target domain that a reasoner wants to understand more fully (Hesse, 1966). There are several cognitive processes employed during analogical reasoning, including selection and retrieval of appropriate source analogs from memory, mapping of objects between source and target, transfer of inferences between the source and target, and learning a more abstract schema that accounts for the common phenomena in both domains (see Figure 1 for an illustration of components used during analogical reasoning). The main focus in this thesis will be on analogical mapping, or finding correspondences between two domains based on their similarity.

Levels of Similarity in Relational Reasoning

Different levels of similarity, including featural, relational, and/or structural, may guide the mapping process (Kroger, Holyoak & Hummel, 2005; Markman, 1997; Markman & Gentner, 1996; Markman & Gentner, 1993; Markman & Gentner, 2000; Spellman & Holyoak, 1992). One way to think about expressing these different levels of similarity is through the use of propositions displayed in predicate form. Thus, we can portray any attribute (e.g., the white chalk) of an object as WHITE(chalk), where white refers to the attribute of the object, chalk. Two objects are featurally similar if they share common attributes (e.g., WHITE(chalk) and WHITE(snow)).

When predicates have more than one slot, they necessarily become more complex (Halford, Wilson & Phillips, 1998), but this complexity allows one to consider relationships among objects relative to a given relationship. For example, the verb CHASE contains two slots: one for chaser and the other for the object being chased. To demonstrate relational similarity one could map two propositions: CHASE(dog, cat) and CHASE(boy, girl). In this case, dog and boy are similar in that they both fulfill the role of chaser, even if they do not share many similar attributes.

Finally, structural/system mapping refer to mappings based on similar higher-order relations coupled with a high degree of one-to-one mapping and structural consistency. One example of system level similarity would be between the Aesop fable, “sour grapes”, and a story about a disgruntled job seeker (Wharton et al., 1994; Wharton, Holyoak, & Lange, 1996). Jumping to get grapes seems fairly different than applying for a job, but the overall consistency in the two relational structures (i.e., person tries to get something, fails to obtain it, then decides

it was not worthwhile) guides one's similarity judgment, whereas the specific attributes and relations play a smaller role in this process.

Structural Alignment and Analogical Comparison

Numerous studies have shown how different types of similarity may guide the mapping process between two domains (Gentner, 2010; Gentner & Wolf, 1997; Krawczyk, Holyoak & Hummel, 2005; Markman, 1997; Markman & Gentner, 1996). One theory of analogical reasoning, called structure mapping theory, is based on the assumption that we construct mental representations of relational structures that are then used to make comparisons between two domains. Objects that share similar roles, yet have different attributes are called alignable differences, since they are different objects, but aligned relationally and structurally. Objects between two domains that are featurally different and do not share common relational roles are called nonalignable differences.

One study performed by Markman and Gentner (1997) investigated how alignability of an object influenced encoding of information between two visually similar scenes, even when the encoding process was incidental (i.e., participants were making similarity judgments between two scenes and were not aware of a later recall test). Markman and Genter used the recall test as a measure of how alignability influences the construction of mental representations. They presented participants with visual recall cues, consisting of objects that were either alignable or nonalignable, where a specific object's alignability condition was counterbalanced across subjects. They found that providing participants with an alignable cue led to a significant increase in number of items recalled from the previous encoding phase of their experiment, thus supporting the notion that structure mapping influences retrieval access to particular information.

The Markman and Gentner finding is important, because we commonly perform analogical mappings, such as while generating hypotheses in science (Dunbar & Blanchette, 2001), looking for supporting precedents for a legal argument (Ashley, 1990; Spellman & Holyoak, 1996; Tenney, Spellman, & Cleary, 2009) and teaching abstract concepts, for example in mathematics (Bassok, 1990; Bassok & Holyoak, 1989). In all of these examples, analogy facilitates knowledge representation among domains that share common relational structures. Understanding how analogies may influence our knowledge representations is therefore crucial for a more full appreciation of how we learn and integrate information across many domains.

Schemas and Knowledge Integration

The study of schemas can help illuminate the relationship between analogical reasoning and knowledge representation. Schemas are generalized knowledge structures – abstracted from multiple examples of experiences – that can be used to guide our encoding of incoming information and potentially influence the types of mental representations that we retrieve from memory (Alba & Hasher, 1983; Bartlett, 1932; Minsky, 1975; Rumelhart & Ortony, 1977; Schank & Abelson, 1977). Integrating information between domains in an analogical fashion may create a more generalized schema that can then be used for problem solving (Gick & Holyoak, 1983). Thus, it is likely that the cognitive mechanisms related to analogical mapping and subsequent memory may be similar to those mechanisms used during the integration of information for schemas.

Two findings from the schema literature that are relevant to this thesis are that people generally have better memory for presented information that is integrated into previous knowledge structures (Bower, Black & Tuner, 1979; Bransford & Johnson, 1972; Pezdek, Whetstone, Reynolds, Askari, & Dougherty, 1989; Schustack & Anderson, 1979), and that

people have a hard time rejecting not-presented items that are consistent with the integrated interpretation of a given scenario (Bower et al., 1979; Thorndyke, 1977; Goodman, 1980). The difficulty in rejecting not-presented, but schema-relevant information is proposed to be a result of a modification of one's experience during encoding and retrieval that would allow one to arrive at a coherent, unified, knowledge-consistent representation of an experience. Therefore, the more likely items could fit into a schema, the more likely people would falsely remember them as being something they have previously encountered (Alba & Hasher, 1983). Recall of schema-relevant information may be enhanced due to a greater association of schema-relevant information among concepts already represented in memory (Anderson & Bower, 1974).

Inhibitory Mechanisms During Retrieval

Although research on schemas has investigated improvement in recall performance for schema-relevant information, fewer studies have looked into why recall for non-schematically relevant information may become worse. One potential cognitive mechanism may be inhibition of information that is not relevant to a schematic knowledge structure. Numerous studies have investigated what is referred to as a retrieval-induced forgetting (RIF) effect (Anderson, Bjork, & Bjork, 2000; Bauml et al., 2009; Storm, Bjork, Bjork, & Nestojko, 2006; Storm & Levy, 2012), where information may become inhibited as a result of competition during retrieval of categorical information.

In most paradigms used to study RIF, participants study several groups of category-exemplar pairs of words (e.g., Fruit—Apple, Fruit—Banana, Tree—Oak, Tree—Fir). After studying all word pairs, participants are then provided with retrieval practice for some of the words in some of the categories, during which they are presented with the category name and then have to perform a stem completion task for the exemplar (e.g., Fruit—A_ _ _ _). One

important aspect is that some categories are not given additional retrieval practice during this phase. Finally, participants are given a category word and asked to list as many exemplar items as they can remember (e.g., list all of the Fruits). Participants are asked to recall items for all categories studied, and the order of the category cue is balanced across participants. One common pattern of results from these experiments is that exemplars benefit from retrieval practice (e.g., Fruit—Apple) by showing improved recall relative to those items that were not included during that phase. More interestingly, for items from categories that were practiced, but were not tested (e.g., Fruit—Banana) participants had worse recall than items from categories that were not practiced at all. Although there is still much debate as to the mechanism, one explanation is that poorer memory performance for items that were from categories used during retrieval practice is due to inhibition of competing information. In the example provided above, when participants see Fruit—A _ _ _ _ , other exemplars from the Fruit category become activated in memory. In order to perform the stem completion and retrieve “Apple”, the other exemplars are weakened. Category membership is an important determinant of whether or not inhibition during the retrieval practice paradigm will occur (Anderson, 2003; Anderson & McCulloch, 1999).

When one makes analogical comparisons between two domains, semantic as well as relational categories may be mentally constructed (Green, Fugelsang & Dunbar, 2006). This finding suggests that relational categorical membership may also influence whether certain items compete or not in memory when performing analogical comparison between two domains. Specifically, those items that share a common relational structure between two domains may inhibit items that do not.

Overview of Chapters

Integrating information from the previously described research on analogical reasoning, schemas, and memory, the current thesis investigates how encoding and retrieval differences guided by analogical comparison influences memory for information contained in the domains used during the analogy. Specifically, this thesis aimed to identify whether memory for information that becomes alignable between two domains changes relative to information that was not used during the analogical mapping process. In addition, this thesis aimed to investigate how different levels of similarity (featural, relational, and structural) may influence subsequent memory of information contained in the analogy.

Chapter 2 describes a series of experiments that investigated how the level of interference during the solving of four-term proportional analogy problems may modify mental representations. In the first two experiments it was shown that reasoners were more likely to falsely endorse a pair of objects as something they had previously seen while solving an analogy if that information was incongruent with the analogical decision. The third experiment expanded this paradigm to demonstrate that poorer memory for interfering information during the analogy was not necessarily due to inhibition of the information; rather, participants were more likely to falsely endorse memory probes whose information was congruent with the structural similarity contained in the previous analogical trial. Findings from this study shed light on how memory for information of features used during analogical reasoning may be influenced by other levels of similarity within an analogy.

Chapter 3 describes two experiments aimed at investigating how retrieval during analogical comparison of two visually complex scenes modifies mental representations for featural information as a function of structural alignability. The first of these experiments

provided support for the possible abstraction of memory for alignable items relative to nonalignable ones, suggesting that featural information may become less accessible if objects between two complex visual scenes are compared based on their shared roles. The second experiment provided evidence that analogical comparison between two scenes differentially influences retrieval of alignable versus nonalignable objects. Specifically, when participants were provided with an alignable retrieval cue during recall, greater alignable versus nonalignable items were recalled, whereas when provided with a nonalignable cue, many more nonalignable items were recalled as compared to alignable items. The results of the second experiment provide empirical support for a “mapping-induced forgetting” effect, such that when given an alignable object as a retrieval cue, memory for nonalignable objects, (i.e., those that do not fit into the relational structure used for analogical comparison become inhibited during retrieval) was worse than when a nonalignable object was used as a retrieval cue.

Finally, Chapter 4 summarizes findings from the thesis, describes potential future directions for each of the experiments, and provides a general conclusion for how the information gained from this thesis may impact theories of knowledge representation, learning, and analogical reasoning.

Chapter Two: Resolving Interference During Analogical Reasoning Modifies Memory

Introduction

A fundamental aspect of higher cognition is the ability to consider relationships among multiple mental representations (Robin & Holyoak, 1995). Being able to manipulate multiple mental representations relies upon the effective interplay of several cognitive processes, including attentional selection of goal-relevant information, integration of multiple relations, and inhibition of irrelevant information. Additionally, relational reasoning is often used to generate inferences about a less familiar target domain; in this case, we also have to retrieve information from memory (Gick & Holyoak, 1980; 1983).

Previous research has investigated the cognitive processes involved in role-based relational reasoning, showing its reliance on the prefrontal cortex (Bunge, Wendelken, Badre, & Wagner, 2005; Christoff, 2001; Krawczyk et al., 2008; Kroger et al., 2002; Morrison et al., 2004; Waltz et al., 1999), both for integrating relations (Cho et al., 2010; Bunge et al., 2005; Wendelken et al., 2008; Green Fugelsang, Kraemer, Shamosh & Dunbar, 2006), and also for inhibition of irrelevant information (Cho et al., 2010; Krawczyk et al., 2008; Kroger, et al., 2002; Morrison et al., 2004).

Understanding how we perform relational reasoning in the face of interference is extremely important. By definition, one special case of role-based relational reasoning, analogical reasoning, is the process of making inferences between two featurally dissimilar domains based on a shared, underlying relational structure. Understanding how irrelevant information is processed during reasoning can shed light on the content and structure of knowledge representations.

As shown in experiments by Cho et al. (2007, 2010), solving analogy trials with interfering information leads to decrements in performance as measured by both response time and proportion of errors. Additionally, having to resolve interference during analogical reasoning interacts with one's ability to process multiple relations. This interaction between inhibition and relational integration has also been demonstrated neurally, involving regions of the PFC associated with behavioral inhibition in a number of other interference paradigms (Aron, Robbins, & Poldrack, 2004; Bauml, Pastotter, Hanslmayr, 2009; Wimber et al., 2008).

Current theoretical models of role-based relational reasoning (e.g., Learning and Inference with Schemas and Analogies (LISA); (Hummel & Holyoak, 1997, 2003, 2005) hypothesize that inhibition is useful for desynchronizing object/role bindings within a given proposition so that when one object/role binding is being activated other object/role bindings are less likely to be processed at that time, thus allowing for clearer mappings between object/role relations across analogs.

The current study aimed to investigate a different type of inhibition that may occur during analogical reasoning. Specifically, we were interested in what happens to information that interferes with one's analogical decision. In previous designs, interference has been shown to lead to increased response time and error while processing analogies, and we hypothesized that resolving this interference may impact information related to interfering dimensions.

Support for inhibition of goal-irrelevant information during the encoding and retrieval of information comes from numerous studies of retrieval-induced forgetting (Anderson et al., 2000; Bauml et al., 2009; Storm, et al., 2006; Storm & Levy, 2012) and directed forgetting (Conway, Harries, Noyes, Racsma'ny, & Frankish, 2000; Macleod, 1999) in the memory literature. In these paradigms information that either competes with successful retrieval, or is deemed unnecessary

for the current task, becomes weakened relative to other goal-relevant information. When reasoning between two domains by analogy, there is bound to be information that is irrelevant. Mental representations of components of each analog that are not relationally alignable may be weakened in a similar fashion, especially when this information interferes with the successful solving of analogies.

The following three experiments were designed to test whether memory is modified for information that is not necessary, or interferes with, the accurate solving of a given analogy. To assess this possibility, we had participants solve analogies that included interfering information. Following each analogy, we tested memory for information by creating memory probes based on components from the analogy task. These probes were modified to reflect changes based on information that was goal-relevant, goal-irrelevant, but non-interfering, or goal-irrelevant and interfering, relative to one's analogical decision. Akin to retrieval-induced forgetting paradigms, perhaps information that interferes when processing the analogy would need to be inhibited to reach an accurate decision regarding whether the two pairs match on a higher-order relation. Thus, we assumed that if information from a component in the analogy were inhibited, then memory for that information should be less accessible during later retrieval for recognition. If so, participants may be more likely to falsely endorse probes based on information that they were unable to reconstruct relative to the components in the analogy problem.

In Experiment 1 we examined whether interference resolution during analogical reasoning is necessary for impacting mental representations of information that is irrelevant for the solving of an analogy. In Experiment 2, we directly compared memory for irrelevant, non-interfering information against irrelevant, interfering information following successful solving of analogies containing interfering dimensions. For both of these experiments, we hypothesized that

resolving interference during an analogy would weaken memory for irrelevant, interfering information as compared to irrelevant information that did not interfere with the solving of the analogy, thus leading to greater false alarms in recognition accuracy.

Experiment 3 tested whether weakening of mental representations for irrelevant, interfering information was due to information being suppressed, or if poorer memory was due to the fact that relational information between the interfering memory probe and participants' most recent analogical decision were identical. Thus, false endorsements for these memory probes could be influenced by whether the information contained in the memory probes would allow for a higher-order relational match, and thus correspond to one's most recent analogical decision. Previous work in our lab (Kroger et al., 2005) suggested that higher-order relational similarity can be abstracted and survives short temporal delays when making analogical comparisons between perceptual objects. In our experimental design, perhaps memory for a particular relational decision was maintained and used for performance on a subsequent recognition task.

We directly tested the inhibition hypothesis supported by results from the first two experiments against a "relational congruence" hypothesis, by having two memory probe conditions be based on information from the interfering dimension in the analogy problems. The second irrelevant, interfering memory probe was still based on the interfering dimension, but did not match the previous analogical decision. Thus, if poorer memory were solely due to inhibition of interfering information, then both of these probes should have similar, high amounts of false alarms. If, however, falsely endorsing the irrelevant, interfering memory probes was due to analogical congruence between one's most recent decision and that of the memory probe, then we would expect that false alarms for the irrelevant, interfering memory probe for which information was not relational congruent would have significantly fewer false alarms.

Overview of Experiments

All of the experiments described in this chapter have the same components: a four-term proportional analogy task, an odd-even distractor task, and a recognition task relating to components from the most recent analogy problem.

People Pieces Analogy Task

The stimuli for the four-term proportional analogy task, and consequently the memory probes for the recognition task, were originally developed in the people pieces analogy (PPA) task by Sternberg (1977), and have since been adapted by Morrison et al. (2001). The stimuli make it possible to systematically vary relational complexity orthogonally with the need for interference resolution while maintaining a constant level of visual complexity (see Figure 2). The PPA task, similar to other analogy tasks, requires mapping the relational structure in one situation onto another. Each term of the analogy problem (A:B :: C:D) in the PPA task consists of a cartoon character that has one value on each of four binary traits (clothing color, gender, height, and width). For all experiments, on each trial one of the traits was randomly chosen as specifying a goal-relevant dimension to which participants were asked to attend. Using only the goal-relevant trait as a dimension for comparison, participants were asked to compare whether the two people in each pair had the same value of a given trait, and then to determine whether the two within-pair relationships matched across pairs. If the two pairs matched on the goal-relevant dimension participants were to respond indicating a valid analogy, otherwise, they were to indicate it was an invalid analogy.

Odd-Even Distractor Task

Following each analogy problem was a brief odd-even distractor task in which participants were asked to indicate whether a number presented on the screen was odd or even.

This task was inserted to reduce rehearsal information contained in the previous analogy trial. The digits shown ranged from one to nine, and each digit in the series was randomly selected, and all were on the computer screen until participants responded, or two seconds, whichever came first. Participants were very good at successfully performing this task (mean accuracy on the distractor task was > 90% for all experiments), and performance on the distractor task was not significantly related to any other variables investigated.

Recognition Task

Following the odd/even distractor task, participants were presented with a pair of cartoon characters from the PPA task. The configurations chosen for the pairs were constrained by the conditions used within each experiment, and thus specific memory probe conditions will be described in fuller detail within each experiment's method section. Across all experiments, participants were asked to indicate whether the pair shown as the memory probe was identical to the A:B pair of the most recent analogy problem. Thus, all recognition memory in the current experiments were confined to the A:B pair for each analogy trial only. If so, they were asked to respond match; otherwise, if the pairs differed on any dimension, they were asked to respond mismatch. Across all experiments, inclusion of a memory trial for analysis was conditional on accurate solving of the analogy problem for that trial.

EXPERIMENT 1

Method

Participants. We recruited 49 (24 female) undergraduate participants through the psychology department participant pool at the University of California, Los Angeles. The participants were in the age range of 18-23 years ($M = 20.5$, $SD = 1.31$). All participants were fluent in English. The participants received course credit in return for their participation. All

experimental procedures were approved by the Committee for Protection of Human Subjects at the University of California, Los Angeles.

Design. As described above, each trial consisted of a four-term proportional analogy problem, an odd/even distractor task, and a memory probe. Each analogy problem consisted of two pairs of human cartoon characters that could be described by four binary dimensions: clothing color (black or white), gender (male or female), height (tall or short), and width (wide or narrow) (see Figure 2). The participants' task was to determine whether or not the analogy was valid, on the basis of a highlighted goal-relevant dimension randomly selected for each trial. The participants were instructed to solve each problem on the basis of goal-relevant traits only. Each analogy was to be classified as valid if the relationship between A:B and C:D was the same regarding the relevant trait.

In Experiment 1, half of the analogy trials contained no interfering dimensions. In this condition, the analogy would be true not only when the relevant trait was taken into consideration, but also when any of the irrelevant traits were taken into consideration. Therefore, even if the participants mistakenly considered any irrelevant traits while solving the analogy, they would not be faced with conflict, nor potentially be misled to the wrong answer. However, for the other half of analogy trials, one of the goal-irrelevant traits had the potential to cause conflict and mislead the participant to an incorrect response. In the example given in Figure 2, the relevant trait is *width* (as indicated by bold font for “width” in the trait list in the third time frame). The relationships for A:B and C:D matched one another (*same width* for A:B equals *same width* for C:D); therefore, the correct response was *valid*. However, a participant who had mistakenly used *color* in solving this problem would be led to conclude that the analogy was false, since the color relationships for pairs A:B and C:D did not match across pairs.

Previous work by Cho et al. (2007; 2010) provided evidence that including irrelevant traits that conflicted with the analogy task lead to significant decrements in performance as measured by accuracy, and response times.

The memory probes chosen for the recognition task in experiment 1 fell into two categories: match and mismatch, each condition occurring for half of all trials. Match memory probes were identical to the A:B pair presented on the most recent analogy problem, and hence, participants should respond *match* to indicate that they remember having seen this pair of characters in the A:B position for the previous analogy problem.

Mismatch probes differed based on changing one feature from one of the irrelevant dimensions (see Figure 2). For those analogy trials containing no interfering dimensions, the mismatch memory probe was altered on any of the irrelevant dimensions (e.g., in the example shown, *height* was an irrelevant, non-interfering dimension, and the memory probe used was similar to the A:B pair, except that one of the characters' value for the height dimension was switched from *tall* to *short*). We balanced the number of times a given irrelevant dimension was chosen for each memory probe across trials, as well as whether the first or second character from the A:B pair was altered for creation of the mismatch memory probe. For analogy trials containing an interfering dimension, the mismatch memory probe was always constructed based on the interfering dimension, in the same way as probes were altered for the irrelevant, non-interfering memory probes.

In Experiment 1, two levels of interference within the analogy problems (Interference vs. No Interference) were combined with two levels of memory probes used for the recognition task (Match vs. Mismatch). The study design was thus a 2 x 2 repeated measures design with 12 valid analogy trials per condition for each participant (a total of 48 true trials). An additional 16

invalid analogy trials were presented, but these were not included in the analysis, as trials with a non-matching relationship were likely to differ in difficulty depending on when the non-exhaustive search for a non-match was terminated. The trials were counterbalanced regarding which trait was selected to be goal relevant, and for which type of memory probe followed a particular goal-relevant trait. Order of analogy trials was pseudo-randomized to ensure that no more than four valid analogy trials occurred in a row.

Procedure. Each trial started with the presentation of an A:B pair to the left of the list of the four traits, for 1700 ms. This was done to ensure that participants encoded the A:B pair along all four dimensions, given that they were not aware of which dimension would be relevant for solving this particular analogy trial. Following this, the A:B pair disappeared, and one of the four dimensions was highlighted in red to indicate its goal-relevance for the trial. After 300 ms, the C:D pair was presented to the right of the four traits, and stayed on the screen until the participants made their decision for the analogy problem, or 6000 ms had passed, whichever occurred first. Labels were placed over the “0” and “1” buttons on the keyboard with “Y” and “N” on them, respectively. Participants were instructed to press the “0” button with their right index finger if the analogy were valid, and to press the “1” button if the analogy were invalid.

Following their analogy decision, a brief visual mask was shown on the screen for 100 ms in order to prevent any residual visual memory of the C:D pair. the visual mask, participants completed the odd/even distractor task (described above), until responding odd or even to each presented digit from the series of numbers one through nine. For the odd/even task, participants were asked to press the “0” key with their right index finger if the number were even, and to press the “1” key with their left index finger if the number were odd.

Finally, participants were presented with a memory probe and were asked to indicate whether this pair was identical to the A:B pair from the most recent analogy problem. Participants were instructed to press the “0” key with their right index finger if the pair were identical to the most recent A:B pair, or to press the “1” key with their left index finger if the pair differed in any way. Once participants had made their memory decision, or after 6000 ms had passed, a brief fixation cross was presented for 1000 ms before the start of the next trial.

The experiment was conducted on a desktop computer, and all the stimuli were presented on a CRT monitor. The experimental software controlling stimulus generation and response collection was implemented in Matlab, using the Psychophysics toolbox. The experiment lasted approximately 40 minutes. The participants were given short breaks during the experimental session.

Results and Discussion

Analogy Performance

Response time (RT) and proportion correct (accuracy) were analyzed as dependent variables. Only the data from correct trials were included in analysis of RT. Also, correct trials with RTs outside the range of 200-6,000 milliseconds (ms) were discarded from the analysis. There were 74 such outlier trials, which represented just 2.4% of the total number of correct trials.

The results for analogy performance, depicted in Figure 3, revealed that performance accuracy decreased for those analogy trials with the need for interference resolution ($M = .77$, $SD = .12$) as compared to analogy trials without any interference ($M = .83$, $SD = .11$). An ANOVA on the analogy accuracy data revealed a significant effect of interference on accuracy, $F(1,48) = 12.24$, $MSE = .007$, $p \leq .001$, $\eta^2_{partial} = .20$.

Processing time increased to engage in interference resolution ($M = 1834.16$ ms, $SD = 401.63$) for analogy trials with interference as compared to those with no interfering dimensions ($M = 1709.24$, $SD = 370.35$). An ANOVA on the analogy RT data revealed that this increase in response time was significant, $F(1,48) = 19.82$, $MSE = 19285.92$, $p \leq .001$, $\eta_{partial}^2 = .29$.

Combined with the analogy accuracy results, these findings replicate the interference effect found in previous studies by Cho et al. (2007, 2010), confirming that adding interfering information in analogy problems lead to decrements in performance as measured by proportion correct and response time for correct trials.

Recognition Memory Performance

Given our hypotheses testing the effect of interference resolution on memory for items used during analogical problem solving, we were primarily interested in whether information that was irrelevant during the solving of an analogy might be more likely to be inhibited during accurate solving of the problem. If this information were inhibited, then participants might be less likely to have an accurate representation of the A:B pair's features for that particular dimension. Thus, when presented with a recognition memory probe, participants would have a harder time discriminating an irrelevant mismatch memory probe from a match memory probe.

We were interested in measuring whether one's ability to discriminate mismatch vs. match memory probe varied as a function of whether the information was unique to interfering information, or was just as likely to occur for information that was irrelevant, regardless of whether it interfered or not. Accordingly, we ran a discrimination analysis on accuracy scores, where the match memory probes would be considered the signal (i.e., something participants had seen before and was in their memory), and the mismatch memory probes considered noise. If interference resolution during analogical reasoning impacts memory for featural information

related to the A:B pair, then we would expect worse discrimination scores for memory probes following an analogy trial with interference as compared to trials without any conflicting information.

As can be seen in Figure 4, participants' discrimination scores were significantly worse for memory probes following analogy trials with interference resolution ($M = .37, SD = .78$) as compared to memory probes following analogy trials with no interference ($M = .87, SD = .90$), $F(1,48) = 7.79, MSE = .757, p \leq .008, \eta^2_{partial} = .18$. This finding supports our hypothesis that information that interferes with the solving of an analogy becomes less accessible during retrieval, thus leading to decrements in memory performance.

Bias scores were not different between interference memory probes ($M = -.17, SD = .61$) and noninterference-based memory probes ($M = -.114, SD = .69$), $F(1,48) < 1, p > .6$. Combined with the results from the d' analysis, this finding suggest that participants were not just more likely to respond "yes" when a memory probe followed an analogy trial with interference resolution; rather, the interference resolution during the analogy impacted the information contained in memory about the A:B pair.

For RT measures of recognition performance, we found that participants were significantly faster when responding to match memory probes ($M = 1600, SD = 511$) than when responding to mismatch memory probes ($M = 1904, SD = 546$), $F(1,48) = 11.57, MSE = 383,693, p \leq .001, \eta^2_{partial} = .20$. All other RT effects were not reliable, F 's $< 1, p$'s $> .4$. These RT results show that participants were faster at accurately recognizing match memory probes, and therefore indicate that differences in memory performance were not solely due to poorer recognition memory performance for the A:B pair's information overall.

EXPERIMENT 2

Experiment 1 provided support for the notion that resolving interference during analogical reasoning modifies memory representations, specifically for those dimensions that interfered with one's analogical reasoning decision. One limitation of the design of Experiment 1 is that, by definition, if an analogy trial had no interfering dimension, we could not test recognition memory for interfering information. Therefore, when comparing irrelevant, non-interfering mismatch memory probes to irrelevant, interfering ones, any differences might also be due to the memory becoming worse after increasing difficulty in the analogy problem. Accordingly, Experiments 2 and 3 were designed to be able to directly test recognition memory for interfering and non-interfering information following successful interference resolution during the analogy.

If our hypothesis from Experiment 1 is correct, then we would expect to find that memory for interfering information should become less accessible than non-interfering information even when both follow analogy problems with interference. Therefore, in Experiment 2, we expected to find that discrimination scores will be significantly worse for mismatch memory probes based on interfering information as compared to those based on non-interfering dimensions.

Method

Participants. We recruited 52 (45 female) undergraduate participants through the psychology department participant pool at the University of California, Los Angeles. The participants were in the age range of 18-23 years ($M = 20.1$, $SD = 1.45$). All participants were fluent in English. The participants received course credit in return for their participation. All

experimental procedures were approved by the Committee for Protection of Human Subjects at the University of California, Los Angeles.

Design and Procedure. The design for Experiment 2 differed from that in Experiment 1 in that all analogy trials in Experiment 2 had one interfering dimension present, and thus all memory probes followed an analogy trial with interference. Memory probes could either match or mismatch the A:B pair from the most recent analogy trial, and thus participants should respond “same” or “different”, respectively. Participants were exposed to all memory probe conditions. There were three types of mismatch memory probes, depending on the dimension on which a character from the A:B pair was modified. Relevant mismatch memory probes were those that were altered based on information in the goal-relevant dimension. Non-interfering mismatch memory probes refer to modified A:B pairs based on a dimension that did not interfere with one’s decision while solving the analogy. Interfering mismatch memory probe are identical to those used in Experiment 1, and refer to memory probes whose information is based on an interfering dimension during the analogy problem.

The procedure for Experiment 2 was identical to that used in Experiment 1. The experiment was conducted on a desktop computer, and all the stimuli were presented on a CRT monitor. The experimental software controlling stimulus generation and response collection was implemented in Matlab, using the Psychophysics toolbox. The experiment lasted approximately 40 minutes. The participants were given short breaks during the experimental session.

Results and Discussion

Analogy Performance

As all analogy trials in this experiment had an interfering dimension, we report descriptively that the average proportion correct ($M = .74$, $SD = .14$), and RT ($M = 1825.66$, SD

= 384.85) were similar to performance accuracy and RT for interfering analogy trials in Experiment 1.

Recognition Memory Performance

We performed discrimination analyses using performance for match memory probes as the signal, and each type of mismatch memory probe as noise. We tested whether poor memory for mismatch following analogy trials with interference resolution was specific to interfering information. Similar to Experiment 1, if memory were worse for mismatch memory probes based on the interfering information relative to the other mismatch memory probes, this would suggest that resolving interference during reasoning would inhibit memory for information that could potentially conflict with one's analogical decision.

As can be seen in Figure 5, we found that participants' discrimination ability was worse for interfering mismatch memory probes ($M = .51, SD = .89$) as compared to both relevant mismatch ($M = .71, SD = .94$) and non-interfering mismatch ($M = .77, SD = .86$) memory probes, $F(2, 102) = 3.28, MSE = .29, p \leq .042, \eta_{partial}^2 = .06$. Planned comparisons indicated that memory for interfering memory probes was significantly worse than both mismatch memory probes, $t's > 2.10, p's \leq .04, \eta_{partial}^2 \geq .07$. Recognition performance for the relevant mismatch and the irrelevant, non-interfering mismatch were not significantly different $t(51) = .69, p > .45$. This finding provides stronger support for the notion that memory for irrelevant, interfering information that is resolved during analogical reasoning becomes less accessible, and thus leads to worse discrimination scores when compared to memory for non-interfering information. The finding that irrelevant, non-interfering mismatch memory probes are more likely to be correctly rejected, and that this rate is not significantly different from relevant mismatch memory probes, suggests that mental representations for information that is irrelevant and interfering (rather than

just irrelevant) during the solving of analogies is what is impacted the most in memory. Bias scores were not significantly different among the three mismatch memory probes, $F(2, 102) = .46$, $MSE = .26$, $p > .6$. Response times for the different memory probes did not significantly differ from one another, $F(2,94) = 2.26$, $MSE = 159256.75$, $p > .10$.

EXPERIMENT 3

The results from Experiments 1 and 2 suggest that memory for interfering information is significantly worse than information that did not interfere in the solving of analogy problems. One explanation is that interfering information becomes inhibited during the solving of the analogy problems, thus leading to less accessibility of this information when asked to retrieve for subsequent recognition. However, an alternative explanation for the findings from Experiments 1 and 2 is based not solely on whether the information interfered, but also what relational information was conveyed by the modified memory probe. Mismatch memory probes that were created based on changing information relative to the interfering dimension from the most recent analogy problem contained information that would have made the previous analogy problem correct, based on that dimension. Referring back to Figure 2, even though participants only have to solve the analogy based on the highlighted, goal-relevant dimension, participants would find the interfering dimension incongruent with their analogical decision if they had paid attention to this information when attempting to match the higher-order relationship between the A:B and C:D pairs.

Support for this interference effect comes from previous studies (Cho et al., 2007, 2010), as well as our results from Experiment 1. All mismatch memory probes were made by changing one character from the A:B pair based on a given dimension. In the case of the interfering dimension, making one change means making the modified memory probe analogically

congruent with the C:D pair. Changing any of the other mismatch memory probes in this way resulted in a memory probe that would not be analogous to the most recent C:D pair. Thus, our previous differences in memory between interfering and other mismatch memory probes could potentially be explained by participants making their recognition memory decision based on the similarity of the modified memory probe's relational correspondence to the C:D pair from the most recent analogy trial.

In Experiment 3 we pitted the “inhibition” hypothesis against the “analogical congruence” hypothesis by creating another mismatch memory probe type from the interference dimension that was not analogous to the most recent C:D pair. If interfering information were inhibited, then both mismatch memory probes based on the interfering dimension should have similar, and relatively worst recognition performance. If, however, memory performance were based on the analogical congruence, then the two interference memory probes should differ, such that the interference memory probe that is not analogical congruent should be much easier to correctly reject on the recognition task.

Method

Participants. We recruited 40 (29 female) undergraduate participants through the psychology department participant pool at the University of California, Los Angeles. The participants were in the age range of 18-23 years ($M = 19.7$, $SD = 1.23$). All participants were fluent in English. The participants received course credit in return for their participation. All experimental procedures were approved by the Committee for Protection of Human Subjects at the University of California, Los Angeles.

Design and Procedure. The design for Experiment 3 was similar to that of Experiment 2, as participants solved analogy problems that all contained an interfering dimension. Memory

probes could either match or mismatch the A:B pair from the most recent analogy trial, and thus participants should respond “same” or “different”, respectively. Participants were exposed to all memory probe conditions. There were three types of mismatch memory probes, depending on the dimension on which a character from the A:B pair was modified. In Experiment 3, we replaced the relevant mismatch memory probe condition with a two-change memory probe, in which the information was changed based on the interfering dimension from the most recent analogy problem. Changing both characters based on the interfering dimension from the most recent analogy problem allowed us to test whether interfering information about the A:B character was inhibited, or whether the high false alarm rates for the interference memory probes in previous experiments was due to the fact that changing these probes lead to a pair of characters that became congruent with the previous analogical decision. All other mismatch probes in previous experiments became incongruent relative to the most recent analogical decision. The remaining memory probes were identical to those in Experiment 2.

The procedure for Experiment 3 was identical to that used in Experiments 1 and 2. The experiment was conducted on a desktop computer, and all the stimuli were presented on a CRT monitor. The experimental software controlling stimulus generation and response collection was implemented in Matlab, using the Psychophysics toolbox. The experiment lasted approximately 40 minutes. The participants were given short breaks during the experimental session.

Results and Discussion

Analogy Performance

As all analogy trials in this experiment had an interfering dimension, we report that, descriptively, the average proportion correct ($M = .77$, $SD = .08$), and RT ($M = 1752$, $SD =$

411.23) were similar to performance accuracy and RT for interfering analogy trials in Experiment 1 and Experiment 2.

Recognition Memory Performance

Three participants were dropped from further analysis, as they did not respond to any of the memory probes for all 64 trials. Thus, analyses based on memory performance were performed for 37 participants.

In Experiment 3 we tested whether it was interfering information, per se, that was inhibited, or whether recognition performance was influenced by how congruent the memory probe is with the previous analogical decision. As can be seen in Figure 6, we found that participants' discrimination ability was worse for interfering mismatch memory probes ($M = .95$, $SD = .91$) as compared to the two-change interfering mismatch ($M = 1.24$, $SD = .83$) and non-interfering mismatch ($M = 1.40$, $SD = .83$) memory probes, $F(2, 72) = 6.42$, $MSE = .30$, $p \leq .003$, $\eta^2_{partial} = .15$. Planned comparisons indicated that memory for interfering memory probes was significantly worse than both other mismatch memory probes, $t's > 2.29$, $p's \leq .02$, $\eta^2_{partial} \geq .08$, and that there was no significant difference between memory performance for non-interfering and two-change interfering mismatch memory probes, $t(36) = 1.26$, $p > .18$. These results suggest that participants' performance on the recognition task cannot be explained by a simple inhibition account. Rather, relational information from the previous analogy trial is maintained between the analogy and recognition tasks, and this information influences participants' memory.

Bias scores were significantly different among the three mismatch memory probes, $F(2, 72) = 3.35$, $MSE = .66$, $p \leq .04$, $\eta^2_{partial} \geq .08$. Response times were also significantly different among the mismatch memory probes, such that irrelevant, interfering mismatch memory probes

took significantly longer ($M = 1917.23$, $SD = 596.11$) than both irrelevant, non-interfering ($M = 1781.90$, $SD = 565.69$) and two-change interfering memory probes ($M = 1805.65$, $SD = 480.53$), $F(2, 72) = 3.983$, $MSE = 110382.24$, $p \leq .022$, $\eta^2_{partial} = .09$. Planned comparisons, showed that irrelevant, interfering mismatch memory probes were significantly slower than both non-interfering, and two-change memory probes, t 's (36) > 2.32 , p 's $\leq .025$, $\eta^2_{partial} = .06$, and that non-interfering and two-change memory probes were not significantly different from each other, $t(36) = .161$, $p > .87$.

General Discussion

Across three experiments, we demonstrated that memory for information used within an analogical reasoning problem may become modified based upon the type of information needed for retrieval. Based on the results of Experiments 1 and 2, it seemed likely that information that was most likely to be impacted following interference resolution during analogical reasoning was that based on the interfering information. Experiment 3, however, provided an alternative explanation based on how relational information from the previous analogy problem may influence one's recognition decision during a subsequent retrieval.

As discussed in our "Overview of Experiments" section, all trials consisted of three components: 1) a four-term proportional analogy problem 2) an odd/even distractor task, and 3) a recognition task. During the analogy task, the A:B pair was never presented at the same time as when the goal-relevant dimension was indicated for each trial. This procedure was meant to ensure that information for all dimensions were encoded, thus leading to greater interference with the interfering dimension than if participants only needed to examine the A:B pair based on the goal-relevant dimension for each trial.

A consequence of this procedure is that the A:B pair had to be held in memory for a relatively long period of time between when it was first presented and when the memory probe was presented, at which point participants had to respond whether this memory probe was identical to the A:B pair that was previously seen. Additionally, in order to solve the analogy problem, participants had to abstract the relational information between the characters in the A:B pair so that they might be able to match these with the relationship between the characters in the C:D pair. Thus, one might expect that recognition performance could be heavily influenced by the relational information shared between the A:B and C:D pair. Thus, when presented with the irrelevant, interfering mismatch memory probe, one might have more familiarity with this object given that it overlaps with their most recent analogical decision.

Previous research by Kroger et al. (2005) suggests that information at the relational level influences how participants respond to “same” or “different” judgments between pairs of visual objects. They found that participants were faster when making “same” judgments when featural and relational decisions overlapped, than when these two decisions were incongruent. This result supports the notion that relational information can influence one’s decision for whether two objects are the same or different. In our experiments, when participants were presented with the memory probe and were asked whether this pair was identical to the A:B pair previously presented, relational similarity could have influenced the amount of familiarity for the given memory probe, thus leading to increased false alarms, as found in all three experiments.

The fact that the two-change interfering mismatch memory probe was correctly rejected at a high rate suggests that the memory effects we found were not necessarily dependent on inhibiting interfering information during the analogy problem. However, we cannot entirely rule out the possibility that these memory effects may be due to both interference resolution and

analogical similarity of the memory probes, as we currently have not tested whether an irrelevant, non-interfering feature that was changed to be congruent with the previous analogical decision would also result in an increase in false alarms relative to the relational incongruent irrelevant, non-interfering mismatch memory probes.

These experiments provide strong support for the hypothesis that memory of visual features used during role-based relational reasoning may become altered as a function of reasoning. Regardless of whether the change occurred due to congruence to the relational decision made on the previous analogy, or to modification due to interference resolution, our results demonstrate that mental representations used during analogical reasoning are changed when they are used for a higher-order cognitive process. These results encourage current theories of analogical reasoning to consider how knowledge structures may be represented and modified as a function of how they are used during the reasoning process. In short, how we reason influences how information is maintained and represented in the mind.

Chapter Three: Analogical Mapping and Mental Representations

People can use analogies to generate knowledge for a novel target situation based on underlying relational similarities to a previously encountered source domain (Gick & Holyoak, 1983; Catrambone & Holyoak, 1989; Keane, 1987; Holyoak & Thagard, 1995). This type of inductive reasoning is useful in myriad aspects of our lives, including generating and explaining scientific theories (Dunbar & Blanchette, 2001), problem solving (Gick & Holyoak, 1980, 1983; Holyoak & Koh, 1987) and decision making (Mather, Knight, & McCaffrey, 2005; Zhang & Markman, 1998).

In making analogical comparisons between the target and source domains, systematic correspondences are identified for objects and relations based on the relational structures representing the two domains (Gentner & Markman, 1997; Gentner, Ratterman & Forbus, 1993; Hummel & Holyoak, 1997; Hummel & Holyoak, 2003). The term “analogical mapping/comparison” will be used in this chapter to describe the process of matching corresponding elements across relational structures. Items may be mapped based on featural similarity, or relational similarity. Featural similarity among items exists when items have overlapping attributes or basic features (e.g., a red apple and red ball are similar because both are the color red and are round). When mapping is based on relational similarity, two objects are similar based on shared relations (e.g., an arrow and a bullet are similar as they are both projectiles and ammunition for weapons). Two matching objects that are superficially different, but aligned in terms of their roles within the overall relational structure in their respective domains, are commonly referred to as alignable differences (Markman & Gentner, 1996; Markman & Gentner, 2000). Items that do not share similar features or roles across two domains are referred to as nonalignable differences (Markman & Gentner, 1996).

Previous research has investigated how making comparisons between two domains draws attention to those items that are alignable differences (Markman & Gentner, 1997; Stilwell & Markman, 2003), and leads to improved memory of those items that are included in the analogical comparison process. In the study of Markman and Gentner (1997), participants were shown two complex visual scenes at the same time, and were asked to rate how similar they were to one another. One scene (referred to as the source) contained two relational structures, and the other contained a relational structure that mapped on to one of these relational structures (across groups, both relational structures were mapped, allowing a comparison of alignable and nonalignable objects regardless of specific item effects). After a 30-minute delay, participants were shown pictures of objects from the source scene and were asked to list as many items as possible from that scene. When the recall cue was an alignable object, participants were able to successfully recall more items than if the object was nonalignable (Markman & Gentner, 1997). These results suggest that comparing the two scenes leads to an increased focus on shared relational structures, resulting in better encoding of objects in the scene thus improving memory when given an alignable object as a recall cue.

The Markman and Gentner (1997) results support an increased attentional focus on alignable differences due to analogical comparison. However, they do not directly address what may happen to our mental representations of objects that become mapped through this process. When information is mapped between domains, knowledge from the source domain is transferred over to the target domain to allow for the generation of inferences that can be used to more fully understand the target domain (Gentner, 2010; Hummel & Holyoak, 2003).

Blanchette and Dunbar (2002) investigated what happens to mental representations of items within the target domain after analogical comparison has been made. Participants in an

analogical comparison group read a target story about the legalization of marijuana first, and then were segued into a story describing alcohol prohibition. A control group only read the target story on legalizing marijuana. A week later, participants were presented with several statements and were asked to indicate if they were from the target story. There were three types of statements: those originally from the target story, those that were from neither story, and those that were modified from the analogous story such that terms referring to alcohol were replaced with marijuana (Blanchette & Dunbar, 2002). This last example was meant to test whether mental representations from the target domain may be modified through analogical comparison of the two stories.

Participants in the analogical comparison group were just as likely to confirm original statements from the target story and reject new phrases that were not from either story, but were more likely to accept that modified sentences supporting analogical inferences between target and source stories were previously seen (Blanchette & Dunbar, 2002). These results suggest that mental representations are modified, specifically for information that is related to inferences generated between the source and target domains.

One reason why participants responded as if they had encountered never-before-seen, but alignable, phrases may be due to abstraction of mental representations from the target domain in order to fit with a more generalized schema supporting both stories (e.g., prohibition of an illegal substance; Gick & Holyoak, 1983; Koh & Holyoak, 1987). Modifying learned information to fit into one's schematic knowledge structure has been studied extensively (Bartlett, 1932; Bransford & Johnson, 1972; Minsky, 1975; Reyna & Brainerd, 1995; Schank & Abelson, 1977), and suggests that our memory for information is influenced by the inferences we generate based on previous knowledge of a given domain.

Markman and Gentner (1997) used a memory test as a probe to show that analogical comparisons guide one's attention and enhance encoding of relationally structured information. However, it is unclear whether memory for information that was relationally mapped is truly episodic or semantic. In Markman and Gentner's study, participants recalled items from a given source scene when presented with an alignable or nonalignable cue. Their finding that participants' improved memory was based on the relational alignability of the recall cue may not fully reveal what may be happening to the representation of objects used during analogical mapping. Perhaps, memory for information that was alignable was more likely to be abstracted as compared to those items that were nonalignable. For example, if participants made an analogical comparison between a pig with a curly tail in the source scene to a baby in the target scene they might just remember having seen a pig in general, and not necessarily remember the features of the originally presented one.

In the current study, we were interested in examining what happens to featural information of mental representations used in analogical comparison. Specifically, we investigated whether memory for information that becomes relationally alignable through analogical mapping of two complex visual scenes is strengthened relative to nonalignable information. If this were the case, what are the mental representations of these two types of objects like? Would participants gain an improvement in episodic memory due to increased encoding of relationally alignable information, or are irrelevant features of alignable information abstracted in memory due to the comparison, thus leaving a trace of the objects encountered as a semantic rather than episodic memory? Answering these questions would provide information about how knowledge structures are represented and altered as a function of analogical comparison.

In order to test whether memory for alignable items differs from nonalignable items, we had participants make analogical comparisons between pairs of complex visual scenes. We separated the source and target scene presentations in time to emulate what often occurs in everyday life: we encounter an unknown target domain and must retrieve information from a previously encoded source domain in order to make analogical mappings between the domains. After making comparisons between source and target scenes containing alignable and nonalignable visual information, participants were given an unrelated distractor task, and then were given a surprise recognition task. Participants were sequentially presented with pictures that corresponded to alignable or nonalignable items previously seen from source scenes, or were close perceptual foils.

One hypothesis is that participants' memory would be enhanced for alignable items as compared to nonalignable items, as more attention would be paid during the analogical mapping process to these items. If so, we would expect to see better recognition for previously seen alignable items and better rejection of perceptual foils matching alignable objects.

An alternative hypothesis is that alignable items may have poorer recognition due to a schematic abstraction of item information to fit into the analogy. If this were true, participants would have worse memory for alignable items compared to nonalignable items, both in terms of hits and false alarms.

EXPERIMENT 1A

Method

Participants. Fifty-nine participants (13 male, mean age 20.36 years old, $SD = 2.598$) at the University of California, Los Angeles participated in the experiment for partial fulfillment of

a course requirement. All participants had normal or corrected-to-normal vision, and were fluent in English.

Design. Two variables were manipulated: alignability (alignable or nonalignable) and recognition object type (valid or foil). Alignability refers to whether objects could be mapped analogically between source and target scenes. Alignable objects were those that shared a similar role across the source and target scene pairs; nonalignable objects did not map across the scene pairs. Object type refers to whether the object presented during the recognition test was presented previously (valid) or not (foil).

Materials. Figure 7 provides examples of the scene stimuli and memory probes used during the surprise recognition test at the end of the experiment. Scenes were modified from those used in Markman and Gentner (1997). There are nine sets of scene triads, where each triad was split between subjects so that each participant only saw a pair of scenes from each set (i.e., the source scene and one of the target scenes). Each source scene had two relational structures, whereas each target scene had only one. Therefore, for each source scene there were two possible target scenes that could be analogically mapped to one of the two relational structures. Objects that shared a relational structure between the source and target scenes are called alignable differences, given that they have different surface features, but share the same role in the scene. Objects that neither shared a common role nor had featural similarity were operationalized as being nonalignable differences. Across groups, objects were equally likely to be alignable or nonalignable, thus controlling for specific item effects when creating the memory probes to be used for the subsequent recognition test. Memory probes were created from objects within the scenes using Adobe Creative Suite software. In total, participants saw 18 scenes and 36 memory probes (18 perceptually-matched foils).

Procedure. The experimental procedure consisted of three parts: a study phase, a 10-minute unrelated, verbal distractor task, and a yes/no recognition test. During the study phase, participants were shown all of the nine pairings of source/target scenes. Participants were presented with each source scene for 5 seconds. At the end of 5 seconds, while the source scene remained on the screen, participants were asked to describe the source scene in their own words as if they were explaining it to someone who had never seen it. This procedure was intended to ensure that participants encoded all aspects of the source scene. After participants had typed in their description of the source scene, they were presented with one of the two target scenes, counterbalanced across participant groups. The order of source/target pairs was randomized across all participants. Participants saw the target scene for 5 seconds, after which they were asked to compare this scene with the previously shown source scene. They were asked to find what makes the two scenes similar and different, and were explicitly asked to describe how they related to one another. This process was then repeated for the eight remaining source/target scene pairs.

After completing an unrelated, verbal distractor task for 10 minutes, participants were given a surprise recognition test on 36 objects (18 perceptual foils) taken from the previously seen source scenes. Objects were randomly presented to participants for two seconds, and they were instructed to press the “Yes” button (covering the “0” key) with their right index finger if the object was identical to one of the objects they had seen in the previous scenes, and to press the “No” button (covering the “1” key) otherwise.

Results

Recognition Performance

Mean percent correct and geometric mean response time were measured. We will report results based on accuracy, as no differences in response time were found among our conditions (p 's $> .3$). Means for percent correct were subject to a two-way analysis of variance (ANOVA), with alignability and object type as within-subject variables. A main effect of object type was found, such that mean accuracy for objects previously seen before ($M = 84.87$, $SD = 11.42$) was significantly greater than for foils ($M = 40.76$, $SD = 19.8$), $F(1, 58) = 188.98$, $MSE = 607.35$, $p < .001$, $\eta^2_{partial} = .77$. An interaction among alignability and object type was also observed, such that for alignable items, alignable objects ($M = 88.12$, $SD = 12.03$) had better recognition than nonalignable objects ($M = 81.63$, $SD = 16.83$), but for perceptual foils, recognition (i.e., correct rejection) was worse for alignable objects ($M = 38.76$, $SD = 21.32$) than for nonalignable objects ($M = 42.77$, $SD = 22.84$), $F(1, 58) = 7.64$, $MSE = 213.06$, $p \leq .008$, $\eta^2_{partial} = .12$.

Discriminability and Bias as a Function of Analogical Mapping

In order to test whether analogical mapping may influence memory, we conducted analyses measuring discriminability and bias scores as a function of alignability. Based on our entering hypotheses, if alignable memory were strengthened due to greater encoding, as suggested by Markman and Gentner (1997), then we would expect higher d' scores for alignable versus nonalignable recognition items. If analogical mapping abstracts information for those items that were alignable, then we would predict worse d' scores and a greater “yes” response bias for alignable versus nonalignable objects.

Figure 8 (a) shows discriminability as measured by d' between previously seen and foil object types. Alignable items ($M = 1.05$, $SD = .99$) were not significantly different from

nonalignable items ($M = .88, SD = .92$), $F(1, 58) = 1.68, MSE = .52, p > .2, \eta^2_{partial} = .02$. The lack of a significant difference between alignable and nonalignable items does not support the hypothesis that analogical mapping improves memory for alignable items.

As can be seen in Figure 8 (b), when measuring bias scores for each condition as a function of alignability, we observed a significant increase in “Yes” responses for alignable items ($M = -.92, SD = 1.18$) than for nonalignable items ($M = -.56, SD = .96$), $F(1, 58) = 4.66, MSE = .79, p \leq .03, \eta^2_{partial} = .07$.

Discussion

In Experiment 1A, we saw that when participants make analogical comparisons between pairs of scenes, their memory for objects that are alignable was different than for those objects that were nonalignable. Although participants had more hits for alignable items that they had seen before, they also had more false alarms, as compared to those items that could not be analogically aligned. Memory for alignable items was not stronger, as there was no difference in discriminability between the alignable and nonalignable objects. Furthermore, we found that participants were significantly biased to indicate that they had previously seen alignable objects, even when presented with perceptual foils.

These findings suggest that memory for alignable information may be altered as a result of analogical mapping. Given that analogical mapping is concerned with comparing objects that share a common role, regardless of differences in featural information, our finding that participants were more likely to be biased to respond “yes” to memory probes regardless of having seen them previously seems to suggest that memory for alignable items may become abstracted. Given that discriminability scores were not worse for alignable, it is unlikely that memory for the alignable objects was completely replaced with an abstracted version. The next

experiment was created to test whether alignable information was completely abstracted relative to nonalignable information as a function of analogical mapping of complex visual scenes.

EXPERIMENT 1B

In Experiment 1B, we tested whether memory for alignable objects is completely abstracted by using a two-alternative forced choice recognition paradigm instead of the yes/no recognition paradigm used in Experiment 1A. If memory for alignable objects were completely abstracted, we would expect to find lower accuracy for alignable objects as compared to nonalignable objects.

Participants and Design. Nine participants (2 male, mean age 19.40 years old, $SD = 3.14$) at the University of California, Los Angeles participated in the experiment for partial fulfillment of a course requirement. All participants had normal or corrected-to-normal vision, and were fluent in English. We manipulated alignability (alignable or nonalignable), which are defined in the same way as in Experiment 1A.

Materials and Procedure. All of the same materials were used as in Experiment 1A. The experimental procedure was very similar to Experiment 1A in that it also consisted of three parts: a study phase, a 10-minute unrelated, verbal distractor task, and a two-alternative forced-choice recognition test. The study phase and distractor task were identical to those in Experiment 1A.

After completing the distractor task, participants were given a surprise two-alternative forced-choice recognition test on 18 pairs of objects taken from the previously seen source scenes. Each object was 500 pixels wide (centered at 300 pixels), and objects on the left side were presented between -50 and -550 pixels, while those on the right side were presented between 50 and 550 pixels, where 0 pixels indicates the horizontal center of the screen. Each pair

of objects and their respective perceptual foil were randomly presented to participants for three seconds, and they were instructed to press the 0 key with their right index finger if the object previously seen before was on the right side of the screen, and to press the 1 key with their left index finger if the object they had seen before was on the left side. Presentation side for the correct choices were balanced across alignable and nonalignable objects, such that each type of object was just as likely to be presented on the left side of the screen as on the right side.

Results and Discussion

We measured proportion correct and response time for correct trials as a function of alignability. If memory for alignable objects were completely abstracted, then we would predict that performance for alignable objects would be significantly worse in the two-alternative forced-choice recognition task. However, we did not find any significant differences in accuracy for alignable objects ($M = .81$, $SD = .18$) as compared to nonalignable objects ($M = .80$, $SD = .19$), $F(1,8) = .02$, $MSE = .033$, $p > .88$, $\eta^2_{partial} = .003$. No difference was found for response times for alignable ($M = 1546.03$, $SD = 297.71$) and nonalignable ($M = 1590$, $SD = 298.76$) objects, $F(1,8) = .23$, $MSE = 37795.40$, $p > .64$, $\eta^2_{partial} = .02$.

The lack of any difference between alignable and nonalignable items in the two-alternative forced-choice paradigm suggests that an extreme abstraction hypothesis for alignable items is not supported. However, given the relatively high accuracy on this task, it seems that the episodic memory corresponding to alignable and nonalignable items is likely to be intact. Combined with the results from Experiment 1A, we suggest that recognition performance consists of two components: retrieval of information that is equally strong for both alignable and nonalignable objects, and a schema relevance bias, such that objects previously aligned are more likely to be endorsed based on familiarity than those that were not used in analogical

comparison. This interpretation follows from research on studies of schema relevance (e.g., Goodman, 1980; Pezdek, et al., 1989; Schustack & Anderson, 1979), which indicate that items that fit into a schema for a particular visual scene are more likely to be recalled, but less likely to be correctly recognized based on specific features. In contrast, worse recall and better recognition for features is found for items in the visual scenes that are schema-irrelevant (Bower et al., 1979; Goodman, 1980; Thorndyke, 1977).

EXPERIMENT 2

In order to test whether recall is better for alignable versus nonalignable objects, we had participants make analogical comparisons between two scenes in a fashion identical to the previous experiments, and then after a delay presented them with a recall cue. The recall cue was either an alignable or nonalignable object they had seen in the previous scenes. Previous research (Markman & Gentner, 1997) suggests that aligning objects based on a similar relational structure would lead to improved recall when provided with an alignable cue. Experiment 2 extends the Markman and Gentner experiment in two ways. First, we separated the source and target scenes in time to examine retrieval of analogical information, rather than guided attention between alignable relational structures when visually comparing two scenes side-by-side, as in Markman and Gentner's procedure. Second, we categorized recall items as either alignable or nonalignable. With this breakdown of recall items, we could test whether alignable cues strengthen items in the same relational structure at the expense of nonalignable items, or whether alignable cues increase memory for all items equally in a scene.

Participants and Design. Twenty-four participants (5 male, mean age 20.75 years old, $SD = 1.94$) at the University of California, Los Angeles participated in the experiment for partial fulfillment of a course requirement. All participants had normal or corrected-to-normal vision,

and were fluent in English. We manipulated alignability of recall cue (alignable or nonalignable), where alignability is defined in the same way as in Experiment 1.

Materials and Procedure. All of the same materials were used as in Experiment 1. The experimental procedure was very similar to Experiment 1 in that it also contained three parts: a study phase, a 10-minute unrelated, verbal distractor task, and a cued-recall phase. The study phase and distractor task were identical to those in Experiment 1.

After completing the distractor task, participants were given a cued recall test on memory for the source scenes they had encountered in the study phase of the experiment. They were tested on the source phase, so that we could test recall for alignable and nonalignable items that were matched between subjects (as each source scene contained two relational structures, one that could be analogically mapped between scenes, and one that could not). Participants were not given a deadline for their recall responses.

Results and Discussion

Recall Performance as a Function of Alignability of Recall Cue

Two raters who were blind to the conditions of the experiment scored participants' responses based on a key created by the experimenter that broke the scenes down into words representing objects that could be found in each scene. The intraclass correlation coefficient for the two raters was 0.96, and on average, scores were only off by 2.3 items ($SD = 1.1$). Recall was scored as a function of alignability of cue to test whether memory was better when cues were fit into the analogical mappings previously made between the source and target scenes.

Additionally, we investigated whether recalled items were alignable or nonalignable, and if the amount of items in these categories differed depending on whether the cue was alignable or nonalignable.

As can be seen in Figure 9, participants' proportion of overall items recalled did not depend on whether the cue was alignable ($M = .45$, $SD = .06$) or not ($M = .50$, $SD = .06$), $F(1, 23) = 2.79$, $MSE = .011$, $p > .12$, $\eta^2_{\text{partial}} = .20$. However, when looking at types of items recalled (alignable vs. nonalignable) as a function of cue (alignable vs. nonalignable), we found a significant interaction $F(1, 23) = 6.8$, $MSE = .05$, $p \leq .024$, $\eta^2_{\text{partial}} = .38$. When investigating simple main effects, we found that information that was previously analogically mapped was just as likely to be recalled if the cue was alignable ($M = .51$, $SD = .17$) or nonalignable ($M = .39$, $SD = .28$), $t(23) = 1.74$, $p > .10$; however, nonalignable information was much less likely to be recalled if the cue was alignable ($M = .39$, $SD = .27$) than if the cue was nonalignable ($M = .61$, $SD = .15$), $t(23) = 2.91$, $p \leq .01$, $\eta^2_{\text{partial}} = .11$. These results suggest that when provided with an alignable cue, participants were less likely to recall items that were nonalignable than when they were presented with a nonalignable cue and asked to recall items from a previously encoded scene.

One possible explanation for these results comes from the retrieval-induced forgetting effect found in retrieval practice paradigms (RIF; Anderson et al., 2000; Bauml et al., 2009; Storm et al., 2006; Storm & Levy, 2012). According to one explanation for RIF, when items from a given category are recalled, other exemplars from that category also become activated, and it is through inhibition of these other items that recalled items become strengthened. Therefore, when testing subsequent recall performance, items that were not practiced, but were from categories containing other items that were, have significantly lower recall than items from categories that were not practiced at all.

Similarly, items that were nonalignable were from the same scene as alignable items. When performing analogical comparisons between the source and target scene during the study phase,

analogical mappings were made between alignable items, thus strengthening them in memory, perhaps at the expense of other items that did not fit into the relational category shared between the two scenes.

General Discussion

We have found evidence for two effects related to analogical mapping and subsequent memory for information that was pertinent to source and target scenes. In Experiments 1A, we found that mental representations of information that is able to be aligned through analogical comparison is treated differently mental representations for items previously seen, but were not able to be aligned. Specifically, we found that if information was alignable, participants were more likely to shift their decision criterion towards falsely endorsing close perceptual foils. This bias was not observed if information was not mapped between source and target scenes. The results from Experiment 1B suggest that memory for alignable items is not completely abstracted from its perceptual features. Rather, the bias observed in Experiment 1A suggests that recognition performance is dependent on a combination of episodic retrieval of information and whether an item bears schematic relevance, where the schema is constructed between the analogous relational structures between the source and target scenes.

The notion of schema relevance and subsequent memory has been extensively studied in text comprehension (Alba, Alexander, Hasher, & Caniglia, 1981; Anderson & Bower, 1974; Britton, Meyer, Hodge, & Glynn, 1980; Gentner, 1981; Thorndyke, 1977), as well as visual memory (Gernsbacher, 1985; Goodman, 1980; Loftus, 1977; Pezdek et al., 1989). Findings from this literature indicate that information that does not conform to schemas is retained with greater discriminative accuracy than is typical or representative information (Anderson & Pichert, 1978; Christie & Schumacher, 1975; Bower et al., 1979; Goodman, 1980).

Results from Experiments 1A and 1B provide support for the hypothesis that analogical comparison between two scenes may create a shared relational structure that interacts with mental representations. Given that we are likely to perform analogical comparisons at many points in our lives, understanding how this may bias our memory is especially critical for theories of problem solving, intelligence, and education.

Experiment 2 provided the first evidence for a mapping-induced forgetting effect, where retrieving information from a source analog influences the retrieval strength of information that is not analogically comparable between the two domains. In the current experiment, participants given a nonalignable recall cue were more likely to produce more nonalignable objects, but recall drastically fell when participants were asked to recall from an alignable cue. This finding suggests that the inhibitory mechanisms involved during other types of retrieval-induced forgetting may occur even when objects are in a relational category defined by shared relational structure, and provides additional evidence for categorization of information during analogical reasoning (Green, et al., 2006a), even if those categories are defined at a structural level (i.e., based on higher-order relational correspondences between the source and target domains).

Overall, this study demonstrates two important facts about how the mind works. One is that the effects of the cognitive processes used during analogical mapping (e.g., retrieving information from memory, creating relational structures and evaluating similarity based on higher-order relational correspondences within working memory) persist beyond analogical mapping. The representation of information that is manipulated during the analogy process may then influence performance for seemingly independent cognitive processes (e.g., a surprise recognition or recall task).

A second conclusion is that cognitive mechanisms supporting retrieval dynamics, such as those used for inhibition of competing information, may apply more extensively than within memory paradigms. If this is indeed the case, we might expect that individual differences related to retrieval inhibition during retrieval practice paradigms would predict the mapping-induced retrieval inhibition found in Experiment 2.

Chapter Four: Summary and Future Directions

The research presented in this thesis demonstrates that performing analogical mapping between two domains – whether they are pairs of objects in a four-term proportional analogical reasoning problem, or objects sharing common roles in two distinct, visual scenes – influences mental representations of information used for the analogy.

The first study (Chapter 1) used a previously studied analogical reasoning task to show that information used for higher-order relational integration between an A:B and C:D pair impacts subsequent memory, such that retrieval depends on whether the information in a subsequent recognition memory probe contains information that would be congruent with one's previous analogical decision. The fact that higher-order information influenced subsequent memory suggests that knowledge representations in memory can be carried over between two distinct tasks. In these experiments, information that was most influenced by false alarms during the recognition task was based on information that interfered with one's decision during a previous analogy problem. This result suggests that interference resolution, already demonstrated to interact with relational integration (Cho et al., 2007, 2010) may also interact with memory of information contained within the A:B pair.

In Chapter 3, we demonstrated that analogical mapping influences memory differentially based on whether mental representations shared common roles between analogs. In these studies, we created a situation in which participants had to recall information from a source scene when mapping information to a relevant target scene presented to them. This procedure is ecologically valid given that analogical comparison often consists of retrieving information from a similar, well understood source domain to better understand a target domain one has previously encountered in the environment (Hesse, 1966).

Across two experiments, we demonstrated that recognition performance for alignable objects following analogical comparison may be influenced by retrieval of the original episodic information, as well as whether the objects were schematically relevant. We found that if objects were schematically relevant between source and target scenes, then participants were more biased to endorse objects as something they had seen, even when shown close perceptual foils. The other relevant finding from this study was that performing analogical mapping between two scenes differentially impacts retrieval of information when presented with a cue that was schematically relevant. Specifically, when participants were given an alignable recall cue they were much less likely to provide nonalignable items in their recall list, as compared to when they were presented with a nonalignable recall cue, suggesting a mapping-induced forgetting effect of nonalignable objects during the analogical mapping stage.

Future studies might aim to explore whether the memory effects found in the first set of experiments are specific to information that interfered with the analogical decision. One follow-up experiment would be to have a full factorial design between irrelevant memory probes (interfering or not interfering) and number of feature changes (one-change or two-change). Crossing these two factors would produce two memory probes that were analogically congruent with the previous analogical decision (interference, one-change and the non interfering, two-change) and two probes that were not (interference, two-change and non-interfering, one-change). Thus, comparing the two analogically congruent memory probes would provide insight into whether the memory effects found are specific to information that interfered during the previous analogy problem, or whether it is mainly driven by the influence of shared higher-order relational information between the previous analogical decision and the information contained in the memory probes.

For the set of experiments presented in Chapter 3, a potential follow-up experiment might test far perceptual foils in the subsequent recognition task. In Experiments 1A and 1B, we found no difference in sensitivity for alignable and nonalignable items. However, we did find that participants were biased to respond “yes” to alignable objects (both valid and foils) on the recognition task more often than nonalignable objects. It would be interesting to test participants on far perceptual foils, perhaps changing the semantic meaning of the object (e.g., if originally presented with a messy pig, have the foil be a messy dog). If recognition memory is equal for alignable and nonalignable objects, as indicated by sensitivity measures as in Experiment 1, then we might predict that providing a perceptually dissimilar foil might enhance recognition performance for alignable items. If schematic relevance is still a factor that influences retrieval, then we might expect sensitivity measures to be similar between alignable and nonalignable items, but find a bias for alignable items (similar to that found in Experiment 1A).

These studies have investigated how our memory may be influenced by the kinds of higher-order cognitive processes that we use, and the results suggest that how we reason and integrate knowledge structures influences how those mental representations are expressed. The findings presented in this thesis provide insights relevant to theories of knowledge representation, analogical reasoning, and retrieval dynamics resulting in inhibition of information in memory. I hope that future studies examine the interplay between shared cognitive mechanisms between reasoning and memory. I will be excited to see the work presented in this dissertation inform these future studies, both in terms of understanding the effects of analogical mapping on subsequent memory, and on the overlap of inhibitory mechanisms across varied cognitive tasks.

Figure 1. Major Components of Analogical Reasoning

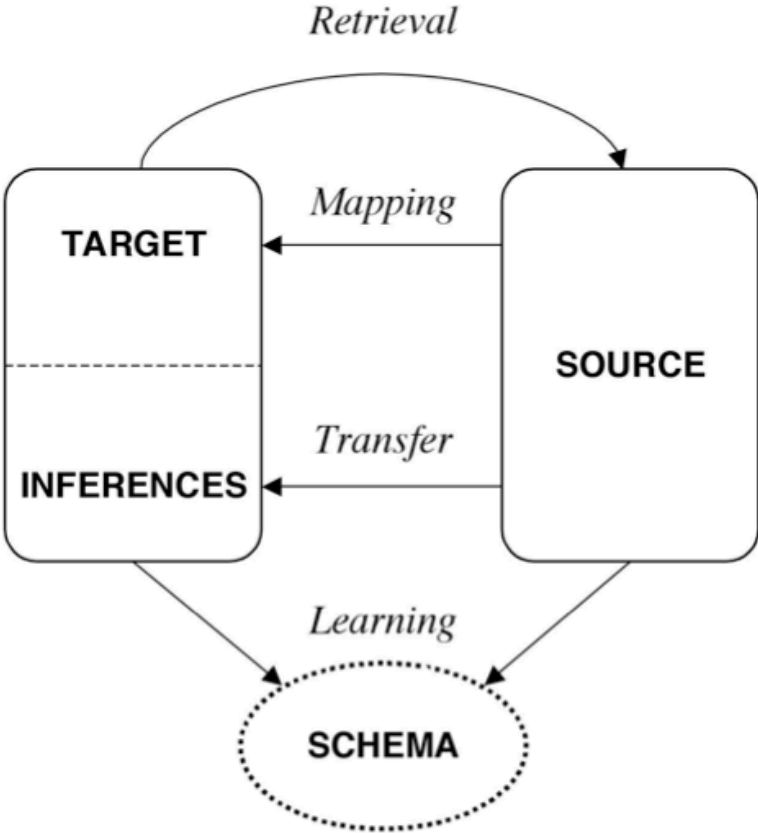
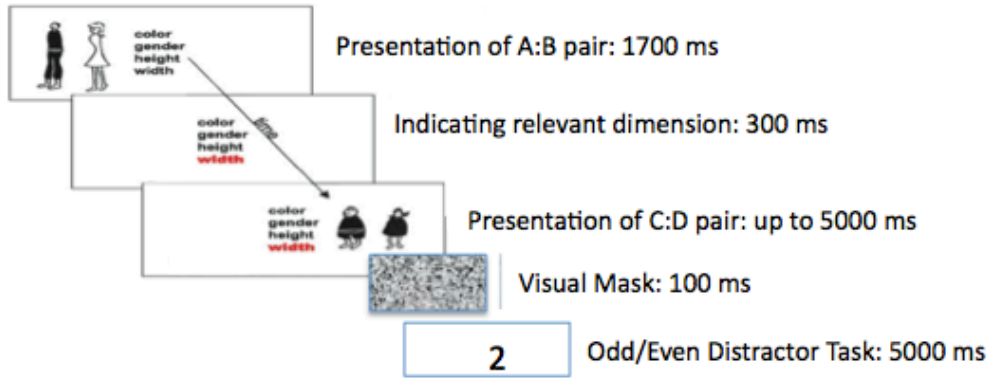


Figure 2. People Pieces Analogy Task



Match
No Change



Dimension Changed:



Non-interfering Height



Interfering Color

Figure 3. Analogy Performance as a function of Interference (Study 1, Exp. 1).

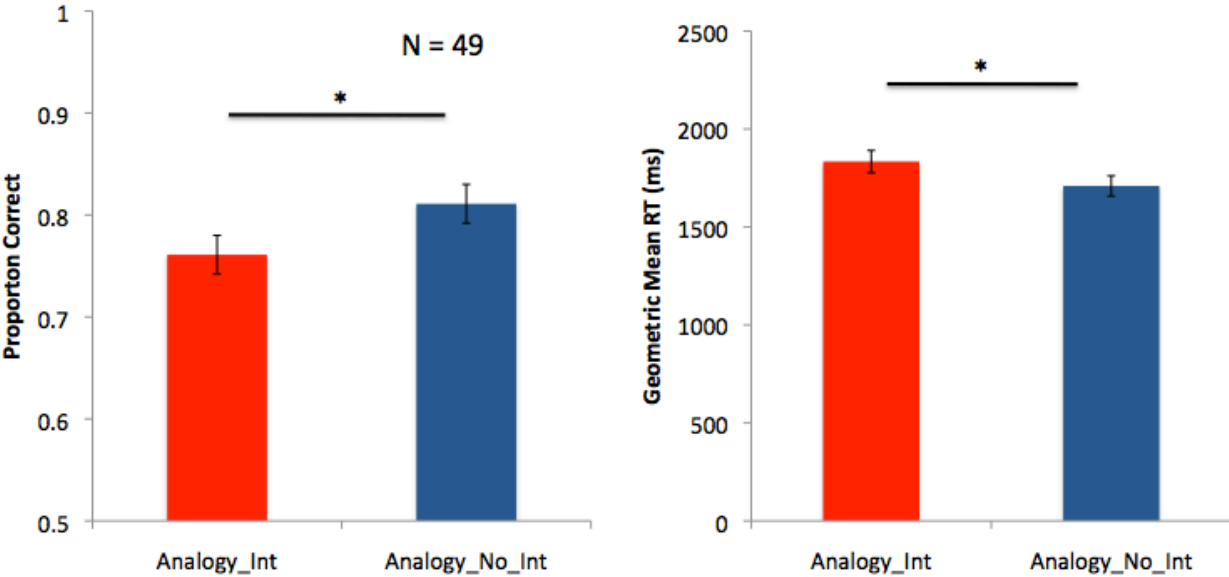


Figure 4. *d'* Scores for Memory as a Function of Interference Resolution (Study 1, Exp. 1).

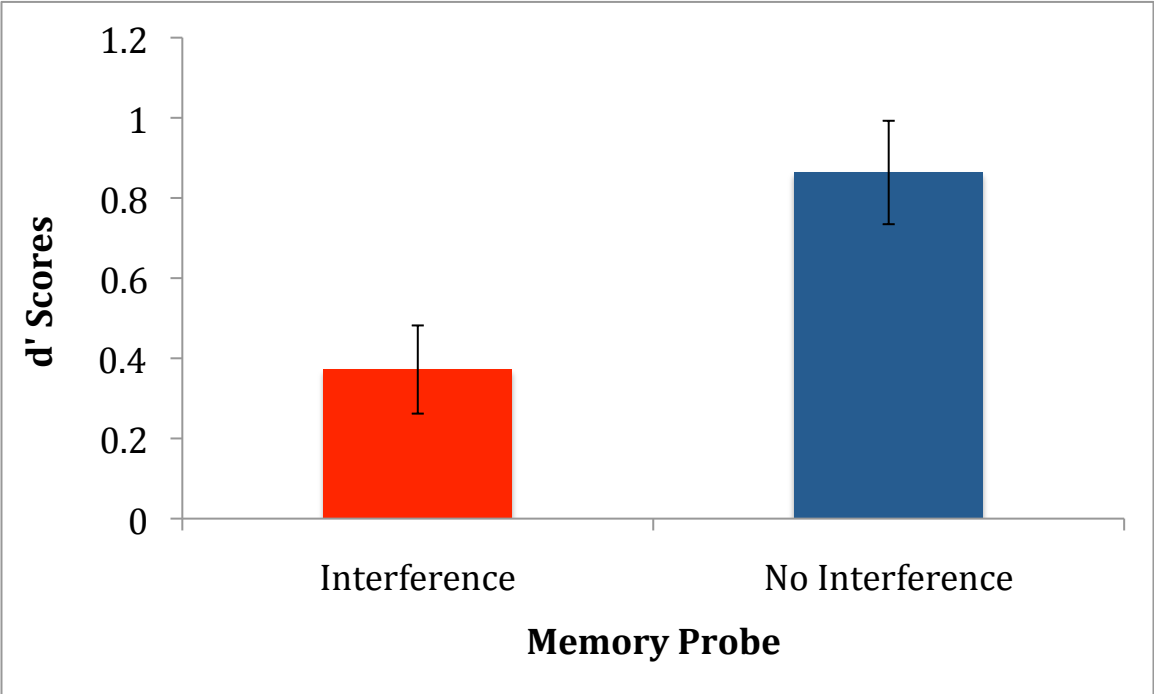


Figure 5. d' Scores for Mismatch Memory Probes following Interference Resolution (Study 1, Exp. 2).

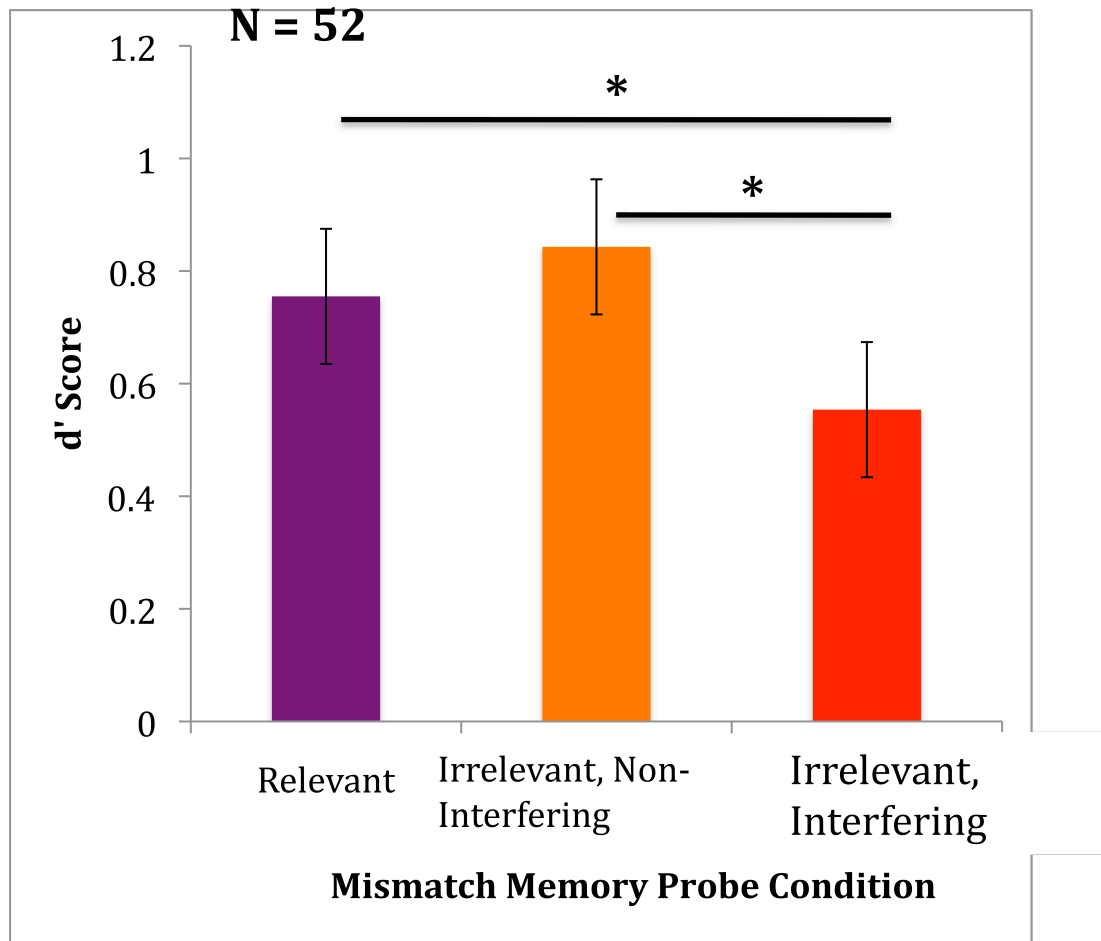


Figure 6. d' Scores for Mismatch Memory Probes following Interference Resolution (Study 1, Exp. 3).

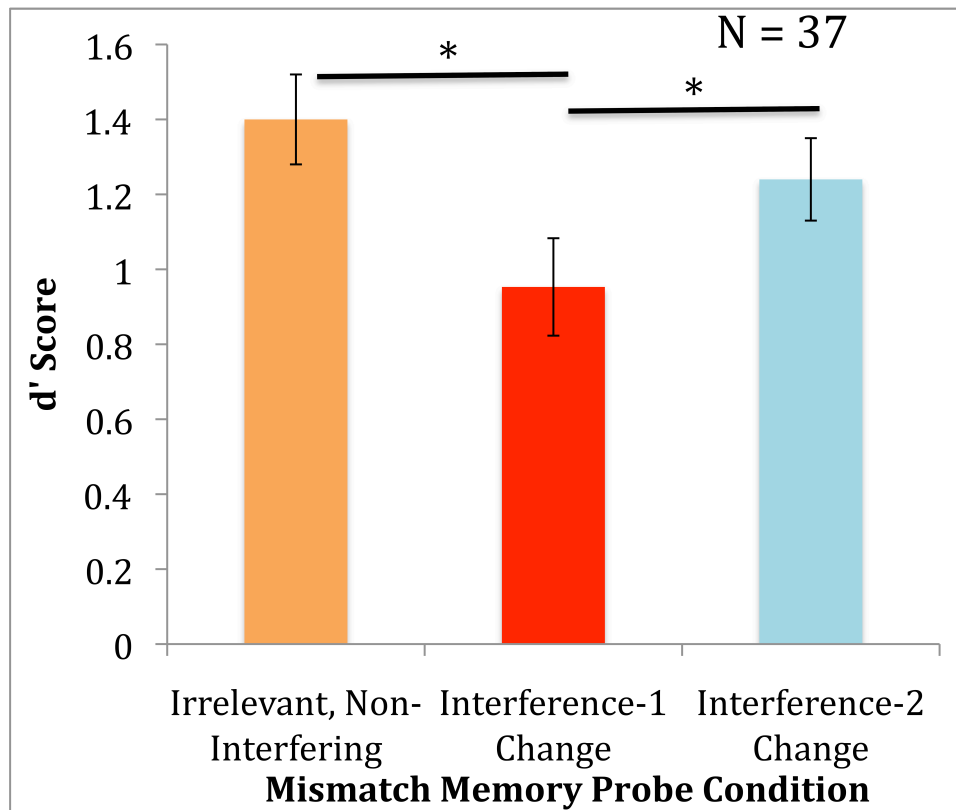


Figure 7. Example Scene stimuli and recognition memory probes (Study 2, Exp. 1)

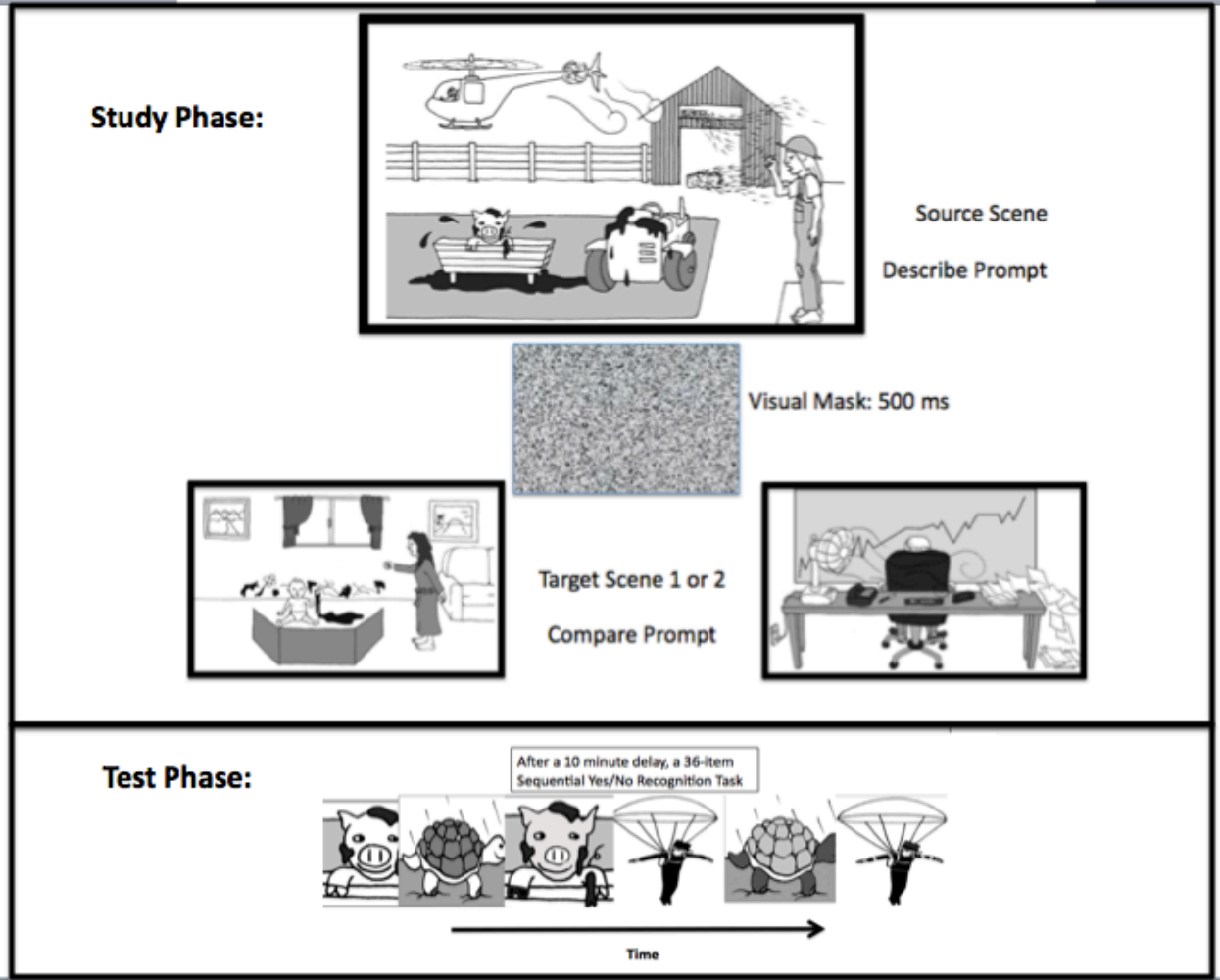


Figure 8. a) d' and b) Bias Scores for Alignable and Nonalignable memory items

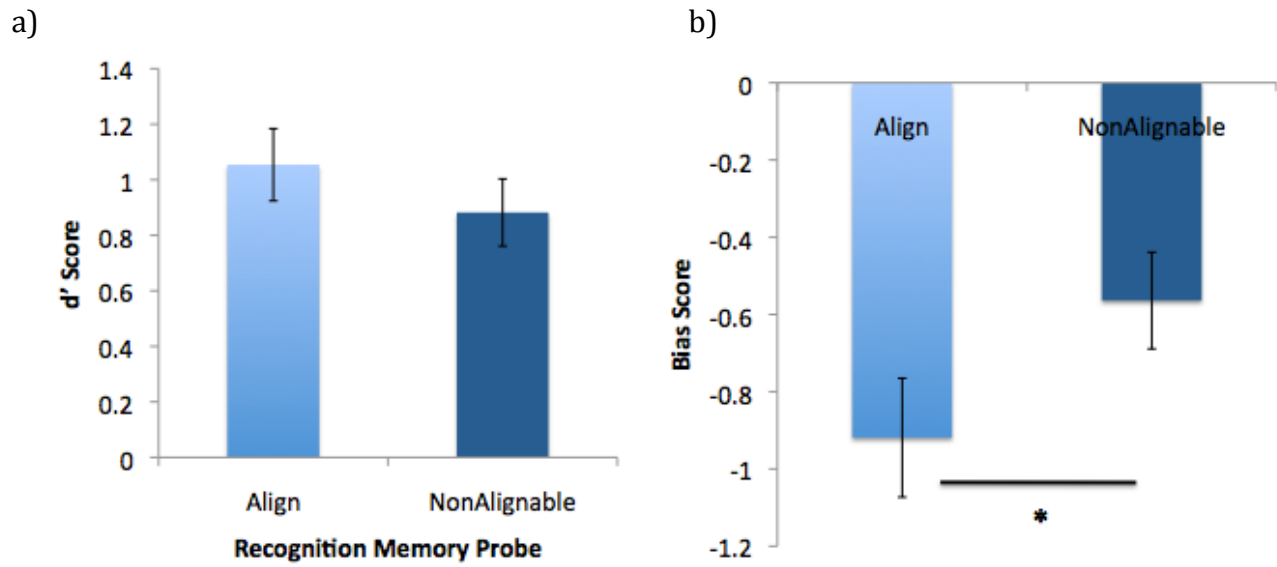
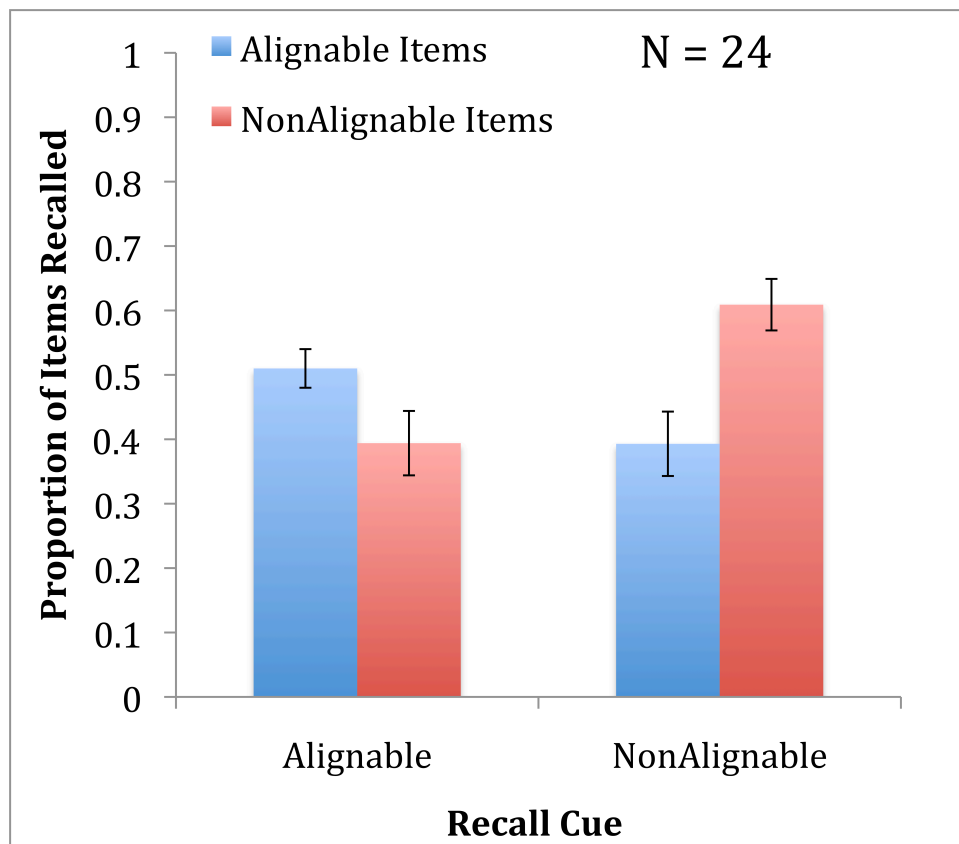


Figure 9. Recall for alignable and nonalignable items as a function of alignable or nonalignable recall cue.



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