

## RESEARCH REPORT

# When Reasoning Modifies Memory: Schematic Assimilation Triggered by Analogical Mapping

Michael S. Vendetti  
Helen Wills Neuroscience Institute, University  
of California, Berkeley

Aaron Wu, Ebi Rowshanshad, Barbara J. Knowlton,  
and Keith J. Holyoak  
University of California, Los Angeles

Analogical mapping highlights shared relations that link 2 situations, potentially at the expense of information that does not fit the dominant pattern of correspondences. To investigate whether analogical mapping can alter subsequent recognition memory for features of a source analog, we performed 2 experiments with 4-term proportional analogies (A:B::C:D), using problems based on cartoon figures varying on 4 visual dimensions. The source analog (A:B) was encoded before the reasoner was told which dimension was relevant to the analogy. After encoding, the A:B pair disappeared, 1 randomly selected dimension was specified as the basis for an analogical decision, and the target (C:D) was presented. A decision about the validity of the analogy was then made, after which memory for the A:B pair was assessed by a recognition test. In Experiment 1, we found that participants' recognition memory was reduced for lures involving a feature change on a dimension initially inconsistent with the analogical decision relative to a change on a dimension that had been consistent with it. The results of Experiment 2 revealed that this memory decrement occurred only when the change in the initially inconsistent feature caused the lure to be coherent with the overall schematic pattern of relational correspondences. These findings suggest that analogical reasoning can trigger changes in the memory representation of a source analog stored in memory such that subsequent recognition is guided by a relational schema.

*Keywords:* analogical reasoning, recognition memory, schema, abstraction

Rather than resembling a finished building, reinforced to stand against time, the trace of an experience initially laid down in memory might better be likened to the early phase of an ongoing construction project. Plans may change, new materials become available—the structure remains a work in progress. Evidence of the constructive nature of memory has accumulated at least since the pioneering work of Bartlett (1932). Memory studies have shown that interventions after the initial experience can bias subsequent recall and recognition (e.g., Higgins & Liberman, 1994; Loftus & Palmer, 1974). As people's attitudes change, their ability to recall their former attitudes diminishes (e.g., Goethals & Reck-

man, 1973; Wixson & Laird, 1976). Eventual outcomes are viewed as having been more foreseeable than was actually the case (the hindsight bias; Fischhoff, 1982). When people play the role of judges deciding a complex legal case, their memory for their initial leaning becomes a blend of their actual first tentative judgment and their subsequent final decision (Holyoak & Simon, 1999). As Simon and Holyoak (2002) have argued, at least some of these apparently similar memory biases may reflect the impact of cognitive mechanisms that tend to maintain coherence of knowledge and beliefs. People not only tend to maintain coherence among beliefs held at a single time, they also tend to maintain (partly illusory) coherence among the beliefs they hold across different times.

An important mental process that may have the potential to reorganize memory is reasoning by analogy. Analogical reasoning involves a structured comparison of two situations, focusing on correspondences between the relations in each (Gentner, 1983; for a recent review, see Holyoak, 2012). Early studies (Gick & Holyoak, 1980, 1983) showed that comparing a known source problem to a novel target problem could generate both a solution to the target and a more abstract schema on the basis of the shared relationships in the two problems. An induced schema can, in turn, foster more robust transfer to additional problems that share the schematic structure (Catrambone & Holyoak, 1989). Moreover, the influence of a schema can be retroactive, facilitating retrieval of an instance that had been stored in memory before the schema

---

This article was published Online First April 7, 2014.

Michael S. Vendetti, Helen Wills Neuroscience Institute, University of California, Berkeley; Aaron Wu, Ebi Rowshanshad, Barbara J. Knowlton, and Keith J. Holyoak, Department of Psychology, University of California, Los Angeles.

This study was part of a doctoral dissertation completed by Michael S. Vendetti under the direction of Barbara J. Knowlton and Keith J. Holyoak. The project was supported by Office of Naval Research Grant N000140810186. We thank Robert Bjork, Jesse Rissman, and Martin Monti for helpful advice at various points during this research.

Correspondence concerning this article should be addressed to Michael S. Vendetti, Helen Wills Neuroscience Institute, University of California, Berkeley, 134 Barker Hall, Berkeley, CA 94720. E-mail: [m.vendetti@berkeley.edu](mailto:m.vendetti@berkeley.edu)

had been acquired (Gentner, Loewenstein, Thompson, & Forbus, 2009; see also Kurtz & Loewenstein, 2007; Markman, 1997). In addition, inferences generated by analogical transfer can become false memories, because people have difficulty discriminating plausible inferences from information that had been presented verbatim (Blanchette & Dunbar, 2002; Day & Gentner, 2007; Perrott, Gentner, & Bodenhausen, 2005; Schustack & Anderson, 1979).

Consider a simple analogy problem in the four-term proportional format A:B::C:D. Processing a four-term analogy requires inferring the unstated relations between A and B and between C and D (Sternberg, 1977; see also Green, Fugelsang, & Dunbar, 2006). These added relations can, in turn, alter similarity relationships (Goldstone, Medin, & Gentner, 1991). The analogy is valid if each (relevant) relation that holds between A and B is the same as the corresponding relation between C and D. The higher order sameness of the A:B and C:D relations is not part of the representation of either the source (A:B) or target (C:D); rather, the higher order relation only arises when the two component pairs are systematically compared and integrated. For example, when evaluating the analogy FATHER : SON :: INVENTOR : INVENTION, a reasoner may compare both pairs to find a relationship that is common to both (e.g., both pairs share the first-order relation "A creates B"). Noticing the sameness of the two first-order relations (a higher order relation constructed on the fly) would lead the reasoner to conclude that the analogy is valid.

Previous studies of the influence of analogical reasoning on memory have focused on the intrusion of specific inferences based on objects and relations in the target that match those in the source. In the present study, we examine memory changes based on mismatched relations between the source and target. People are able to make use of imperfect analogies to solve problems (Holyoak & Koh, 1987). In complex analogies of the sort often used in teaching scientific concepts (e.g., the analogy between cell biology and a factory), only some of the relations in the source and the target are the same (e.g., both factories and cells produce important products to be used elsewhere), whereas others differ (e.g., cells increase in number by division of existing cells, whereas factories grow by separate construction of new factories). According to the multiconstraint theory of analogical mapping (Holyoak & Thagard, 1989, 1995), people use a constraint satisfaction mechanism to find the best compromise between multiple pressures that may partially conflict. In general, people tend to arrive at a mapping that yields a satisfactory degree of overall coherence but, in the process, may generate incorrect inferences because of overapplication of a partially valid analogy (Gentner & Gentner, 1983).

If the source and target are presented together for comparison, aspects of an analog that do not cohere with the dominant mapping (termed *nonalignable differences*) are likely to receive reduced attention and hence be less useful as retrieval cues on a subsequent memory test (Markman & Gentner, 1997). But what is the fate of aspects of a source analog already stored in memory that are inconsistent with the dominant relations that determine the mapping with a target analog? One possibility is that such inconsistencies, which are likely to be actively inhibited during the mapping process (Cho et al., 2010; Richland, Morrison, & Holyoak, 2006; Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004), will be rendered inaccessible. In various memory para-

digms, information that either competes with successful retrieval or is deemed unnecessary for the current task, becomes weakened relative to goal-relevant information, a phenomenon termed *retrieval-induced forgetting* (e.g., Anderson & Spellman, 1995; Bäuml, Pastötter, & Hanslmayr, 2010; Storm & Levy, 2012). Perhaps information that mismatches an analogical decision is similarly rendered inaccessible. Although such retrieval-induced forgetting is most readily demonstrated in memory recall tasks (Butler, Williams, Zacks, & Maki, 2001; Perfect, Moulin, Conway, & Perry, 2002), it has also been demonstrated in tests of recognition memory, consistent with the hypothesis that competing memory representations are actively inhibited and not simply more difficult to recall (Gómez-Ariza, Lechuga, Pelegrina, & Bajo, 2005; Hicks & Starns, 2004; Verde & Perfect, 2011). According to this view, information in the source that is inconsistent with mapped relations would be inhibited to facilitate mapping with the target. For example, in considering the analogy between the solar system (source) and an atom (target), the reasoner must retrieve information about the source that supports the mapping (e.g., smaller bodies orbit a larger one), which may, in turn, inhibit information about the source in memory that is inconsistent with the mapping (e.g., planets, unlike electrons, rotate about their axes).

An alternative possibility is that mismatching aspects of the source will sometimes be altered to increase coherence with the dominant analogical relations. This possibility is consistent with Bartlett's (1932) hypothesis that inconsistent information is often assimilated to a general schema. Perhaps the relations that support an analogical decision act as a *de novo* schema (Gick & Holyoak, 1983). A source relation that mismatches this emerging schema may, in essence, be revised so that it coheres with it, setting the stage for predictable memory errors. According to this hypothesis, considering the analogy between the solar system and the atom might actually alter the representation of the solar system in memory to make it more consistent with the structure of the atom (e.g., leading to doubt that planets rotate around their axes).

We conducted two experiments to test recognition memory for source information that were either consistent or inconsistent with an analogical schema. In Experiment 1, we aimed to assess whether memory for inconsistent information is impaired; in Experiment 2, we sought to distinguish between the inhibition and assimilation hypotheses.

## Experiment 1

### Method

**Participants.** Fifty-two (45 female) undergraduate participants were recruited through the Psychology Department participant pool at the University of California, Los Angeles (UCLA). The participants were 18–23 years old ( $M = 20.1$  years,  $SD = 1.45$ ). All were fluent in English. They received course credit in return for their participation. All experimental procedures were approved by the Committee for Protection of Human Subjects at UCLA.

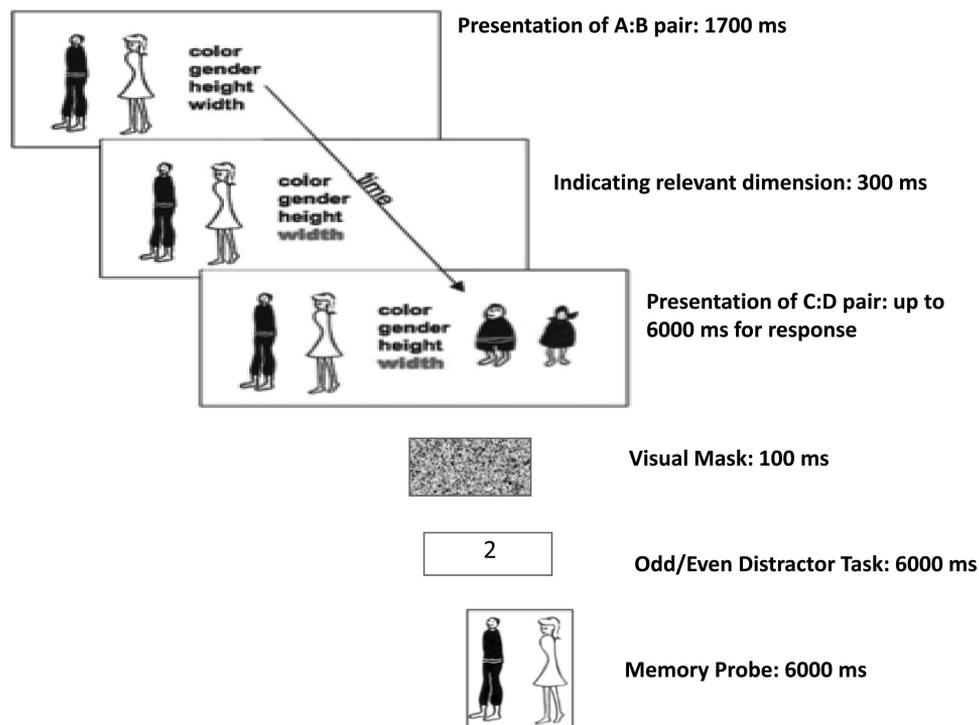
**Materials.** Experiments 1 and 2 had the same basic components: a four-term proportional analogy task, an odd–even distractor task, and a recognition task relating to components from the most recent analogy problem. The stimuli for the four-term para-

portional analogy task and for the memory probes used in the recognition task were based on the people-piece analogy (PPA) task used by Sternberg (1977) and later adapted by Morrison, Holyoak, and Truong (2001). The PPA task, like other proportional analogy tasks, requires mapping the relational structure in a source analog (A:B pair) onto a target (C:D pair). These stimuli (see Figure 1) make it possible to systematically vary factors that influence the difficulty of analogical reasoning while maintaining a constant level of visual complexity (Cho et al., 2007, 2010; Viskontas et al., 2004). Each term consists of a cartoon character that has one value on each of four binary traits (clothing color, gender, height, and width). These stimuli make it possible to distinguish between a *relevant* dimension that determines the analogical decision and *irrelevant* dimensions that are to be ignored. Moreover, the irrelevant dimensions can either be *consistent* or *inconsistent* with the analogical decision. By creating lures involving changes to the A:B pair based on one of these different types of dimensions, we sought to determine whether analogical mapping can alter memory for the source analog.

**Design.** Each trial consisted of a four-term proportional analogy problem, an odd–even distractor task, and a memory probe (see Figure 1). 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). The

participants' task was to determine whether the analogy was valid on the basis of one highlighted goal-relevant dimension, randomly selected for each trial. Each analogy was to be assessed as valid if the relationship between A:B and C:D was the same for the relevant trait. Participants were instructed to solve each problem on the basis of one goal-relevant trait only. Two of the irrelevant dimensions were consistent, in that they also matched the structure of the relevant dimension (e.g., if A and B were the same on the relevant dimension, they were also the same on two irrelevant dimensions). The third irrelevant dimension was inconsistent (e.g., if A and B were the same on the relevant dimension, they would be different on the inconsistent dimension). For example (see Figure 1), if the relevant dimension on a trial was width and A and B were the same in width (as were C and D when the analogy was valid), then two of the other dimensions would also be the same for the A:B pair (e.g., gender and height), but the pair would be different on the fourth dimension (e.g., clothing color). In total, there were 60 analogy trials, consisting of 45 true and 15 false trials. All recognition data are based on valid analogy trials that were answered correctly.

The difficulty of the PPA task is known to increase with relational complexity, defined as the number of relevant dimensions (Viskontas et al., 2004). In the present study, all trials involved just one relevant dimension, thus minimizing relational complexity. Because all analogy trials included one inconsistent dimension, all



*Figure 1.* Example of a trial in the study. Each trial consisted of an analogy problem, in which participants had to respond on the basis of whether the A:B pair shared a higher order “same” relationship with the C:D pair for the highlighted dimension (in this example, “width”). After the analogy decision, participants were presented with a brief visual mask, followed by an odd–even distractor task, and then they were presented with a memory probe. Participants were asked to indicate whether the pair of characters in the memory probe was identical to the A:B pair shown on the most recent analogy trial. Note that in a given trial the A:B pair disappeared after 1,700 ms and is left here for illustrative purposes only.

memory probes followed an analogy decision that had involved potential interference from that inconsistent dimension.<sup>1</sup> Memory probes could either match or mismatch the A:B pair, and participants were instructed to respond “same” or “different,” depending on whether the probe was identical to the source analog, A:B. There were a total of 15 match memory trials and 45 mismatch lure trials. Match probes (Type I; see Figure 2) were identical to the A:B pair from the most recent analogy trial. Lures always differed from the presented A:B based on one changed feature for one dimension. As shown in Figure 2, Experiment 1 included three types of lures, each formed by changing one object’s value on a given dimension. Relevant–inconsistent lures (Type II) were created by changing the value of one object on the one relevant dimension (in the example used in Figure 2, Object A on width). Irrelevant–inconsistent lures (Type III) were created by changing one feature of one object on an irrelevant dimension that had initially been consistent with the relevant dimension. Irrelevant–consistent lures (Type IV) were created by changing one feature of one object on an irrelevant dimension that had initially been inconsistent with the relevant dimension, so that the lure is more consistent with the analogical schema.

**Procedure.** Each trial began with the presentation of the A:B pair to the left of the list of the four traits, for 1,700 ms, after which the A:B pair disappeared. This procedure ensured that participants would be motivated to encode the A:B pair on all four dimensions, as participants did not know which dimension would be relevant for solving this particular analogy trial until after the A:B pair had been removed. After its disappearance, one of the four trait names was highlighted in red to indicate it was the dimension relevant for the analogical decision on that trial. After 300 ms, the C:D pair was presented to the right of the four traits’ names and stayed on the screen until the participant made a decision for the analogy problem, or 6,000 ms had passed, whichever occurred first. Labels with *Y* and *N* on them were respectively placed over the *O* and *I* keys on the keyboard. Participants were instructed to press the key labeled *Y* with their right index finger if the analogy was valid and to press the key labeled *N* if the analogy was invalid.

Following their analogy decision, a brief visual mask was shown on the screen for 100 ms to eliminate any residual visual memory for the C:D pair. Following the visual mask, participants completed an odd–even distractor task, indicating whether the number presented on the screen was odd or even. This task was intended to minimize verbal rehearsal of the A:B pair. The presented digits were randomly selected from the range of 1 to 9. Digits were presented sequentially, and each digit remained on the computer screen until the participant responded or 2 s elapsed, whichever came first. The next digit then appeared. Participants performed this distractor task (which lasted 10 s) with high accuracy (mean correct > 90% for both experiments), and performance on this task was not significantly related to any other variables investigated.

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 (yes–no recognition test). Participants were instructed to press the key labeled *Y* with their right index finger if the pair were identical to the most recent A:B pair (“old”) or to press the key labeled *N* with their left index finger if the pair differed in any way. Once participants had made their memory decision or after 6,000 ms had passed, a brief

fixation cross was presented for 1,000 ms before the start of the next trial. Both accuracy and response time (RT) were measured.

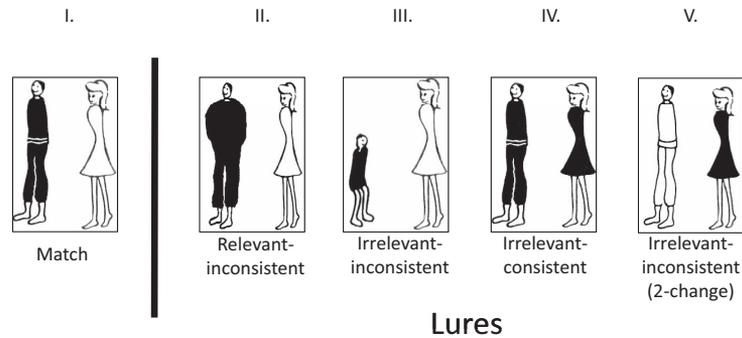
The experiment was conducted on a desktop computer, and all of the stimuli were presented on a CRT monitor. The experimental software controlling stimulus generation and response collection was implemented in Matlab, using the Psychophysics toolbox (Brainard, 1997). The experiment lasted approximately 40 min. Participants were given short breaks during the experimental session.

## Results and Discussion

For analogy decisions, the average overall proportion correct ( $M = .74$ ,  $SD = .14$ ), and RT ( $M = 1,825$  ms,  $SD = 385$ ) were similar to performance levels obtained in previous studies using similar materials and procedures for analogies with one interfering dimension (Cho et al., 2007, 2010). Figure 3 presents proportion of “old” responses for all probe types (i.e., proportion correct or hit rate for match memory probes, and error or false alarm rate for each type of lure). The relatively low overall rate of “old” responses is consistent with the 3:1 ratio of “new” probes (lures) to “old” probes (match pairs) in the design of Experiment 1 and presumably reflects an overall bias to respond with the more frequent correct label (“new”). We used signal detection analysis to compute  $d'$  values; because the design included only one type of probe (Type I) that yielded hits,  $d'$  differences are (inversely) monotonically related to comparisons based on the corresponding measure of false alarms for the three types of lures (plotted in Figure 3). As can be seen in Figure 3, participants were less able to discriminate irrelevant–consistent lures ( $M = .51$ ,  $SD = .89$ ) as compared with both relevant–inconsistent lures ( $M = .71$ ,  $SD = .94$ ) and irrelevant–inconsistent lures ( $M = .77$ ,  $SD = .86$ ),  $F(2, 102) = 3.28$ ,  $MSE = .29$ ,  $p = .04$ ,  $\eta_p^2 = .06$ . Planned comparisons indicated that discrimination ability was significantly worse for irrelevant–consistent lures than for either of the other lure types,  $t(51) > 2.10$ ,  $ps < .04$ ,  $\eta_p^2 = .07$ . Recognition performance did not differ significantly between relevant–inconsistent and irrelevant–inconsistent lures,  $t(51) = 0.69$ ,  $p > .45$ ,  $\eta_p^2 < .01$ . Response times for the three types of lures did not differ reliably,  $F(2, 100) = 2.58$ ,  $MSE = 241,029$ ,  $p > .08$ ,  $\eta_p^2 = .04$ .

The results of Experiment 1 thus revealed that recognition memory was significantly poorer for irrelevant–consistent lures compared with either of the other two types of lures, both of which were inconsistent with the relation (same or different) for the relevant dimension of the actual A:B pair. Consistent and inconsistent lures both were based on a single change from the source analog, but the consistent lures were significantly harder to reject than the inconsistent lures. This finding indicates that featural information in a source analog that is inconsistent with the overall

<sup>1</sup> A pilot study investigated memory for featural information following analogy trials with and without an inconsistent dimension. Replicating Cho, Holyoak, and Cannon (2007; Cho et al., 2010), participants were significantly less accurate in solving analogy problems when an inconsistent dimension was present,  $F(1, 48) = 12.24$ , mean square error ( $MSE$ ) = .007,  $p < .001$ ,  $\eta_p^2 = .20$ . In addition, participants’ ability to discriminate valid memory probes from perceptual lures was significantly impaired following trials with an inconsistent dimension (when the lure involved the inconsistent dimension) compared with trials without any inconsistent dimensions,  $F(1, 48) = 7.79$ ,  $MSE = .757$ ,  $p = .008$ ,  $\eta_p^2 = .18$ .



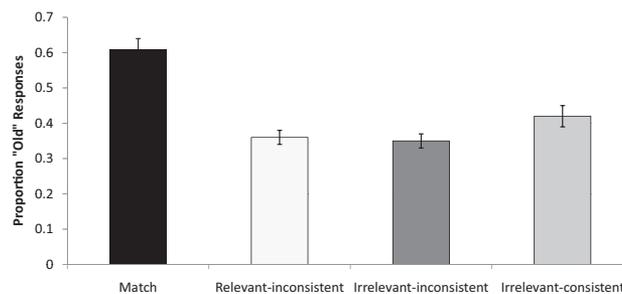
*Figure 2.* Examples of memory probes used in the two experiments, based on the A:B and C:D pairs shown in *Figure 1*. Match memory probes (I) were pairs of characters identical to the A:B pair from the most recent analogy problem. Relevant–inconsistent lures (II) were created by changing the value of one object on the one relevant dimension (in this example, Object A on width) so as to differ from the actual A:B pair. Irrelevant–inconsistent lures (III) were created by changing one feature of one object on an irrelevant dimension that had initially been consistent with the relevant dimension (Object A has changed in height, a dimension along which A and B had initially been the same, consistent with their sameness on width). Irrelevant–consistent lures (IV) were created by changing one feature of one object on an irrelevant dimension that had initially been inconsistent with the relevant dimension (Object B has changed in clothing color, yielding a lure in which A and B are the same on a dimension that they had initially differed, so that the lure is more consistent with the analogical schema). Irrelevant–inconsistent two-change lures (V) were created by changing one feature of A and one feature of B on an initially inconsistent dimension (clothing color has been changed for both A and B, resulting in a lure in which A and B differ in clothing color). The two changes maintain the inconsistency between the irrelevant dimension in the presented A:B pair (A and B differed in clothing color) and the relevant dimension (A and B were the same in width). Match probes (I) were used in both experiments. Experiment 1 included lures of Types II, III, and IV; Experiment 2 used Types III, IV, and V.

schema supporting the analogy becomes less discriminable in memory following successful analogical comparison. Experiment 2 was designed to test alternative explanations of this phenomenon.

### Experiment 2

The results of Experiment 1 indicate that recognition memory for visual features of a source analog (A:B pair) is impaired if the lure changes a feature on an irrelevant dimension that initially was in relational conflict with the basis for the analogical decision, thereby transforming what had been an inconsistent relation in the source into a consistent relation in the lure. Experiment 2 was

designed to test two alternative explanations for this finding. The inhibitory hypothesis assumes that because an inconsistent relation in the source interferes with solving the analogy problem, this interfering information must be actively inhibited during the analogical mapping process; as a consequence, accessibility of this information is reduced on a subsequent recognition test. In contrast, the schematic assimilation hypothesis assumes that reasoners assimilate inconsistent dimensions to the relational schema supported by the analogy and use this relational information as a basis for their recognition judgments. In Experiment 1, a memory lure based on the initially inconsistent (i.e., potentially interfering) dimension necessarily was consistent with the relation that determined the analogical decision (because changing one feature of



*Figure 3.* Proportion of “old” responses in Experiment 1. Participants were significantly more likely to falsely endorse irrelevant–consistent (Type IV) lures relative to relevant–inconsistent (Type II) or irrelevant–inconsistent (Type III) lures. (See *Figure 2* for examples of all probe types.) Error bars represent standard error of the mean.

one object on that dimension necessarily resulted in a consistent lure). If participants had assimilated the relational schema into their memory representation for the source analog, then discriminability would have been selectively impaired for the irrelevant-consistent lures, as we observed.

In Experiment 2, we pitted the inhibitory hypothesis against the schematic assimilation hypothesis by creating another type of lure based on the initially inconsistent dimension. By changing one feature on the inconsistent dimension for both Objects A and B (rather than just one of them), the inconsistent relation will be preserved in the lure rather than altered to be consistent with the relevant analogical relation (see Figure 2, Type V). The schematic assimilation hypothesis predicts that a mismatch on an initially inconsistent dimension formed by two feature changes (one on Object A and one on Object B) will be easier to reject than a mismatch based on just one feature change (i.e., irrelevant-consistent, Type IV lure). In contrast, if the initially inconsistent dimension is subject to inhibition following the analogical comparison, then people would be expected to suffer reduced discriminability for any type of lure involving that dimension (i.e., recognition performance for Types IV and V would be equally impaired relative to Type III). In other words, if clothing color is inhibited (as width is the critical relevant dimension), then it shouldn't matter whether a lure involves a change in the clothing color of a single character or both. In contrast, if participants' memory decisions are based on schema assimilation, there should be more false alarms when the changes to clothing (i.e., the inconsistent, irrelevant dimension) become consistent with the schema activated by the A:B pair.

## Method

**Participants.** Forty (29 female) undergraduate participants were recruited through the UCLA Psychology Department participant pool. The participants were 18–23 years old ( $M = 19.7$  years,  $SD = 1.23$ ). All were fluent in English. They received course credit in return for their participation.

**Design and procedure.** The design of Experiment 2 was very similar to that of Experiment 1. There were three types of lure, depending on which dimension of the A:B pair was modified. The relevant-inconsistent lure (Type II) included in Experiment 1 was not used. Instead, we added a *two-change* irrelevant-inconsistent

lure, for which one feature change in each of two objects created a lure that preserved the relation in the original A:B pair (see Figure 2, Type V). The other two types of lures—irrelevant-inconsistent, based on one change (Type III), and irrelevant-consistent, based on one change (Type IV)—were the same as those tested in Experiment 1. Thus all lures used in Experiment 2 were derived from a dimension that was irrelevant to the analogical solution. The equipment and procedure for Experiment 2 were identical to those used in Experiment 1.

## Results and Discussion

The overall average proportion correct ( $M = .77$ ,  $SD = .08$ ) and RT ( $M = 1,752$  ms,  $SD = 411.23$ ) on the analogy task were similar to accuracy and RT for analogy trials in Experiment 1. Three participants were dropped from further analysis, as they did not respond to any of the memory probes for all 60 trials. Thus, analyses of recognition memory performance are based on 37 participants.

Figure 4 presents the proportion of “old” responses for all probe types (i.e., proportion correct or hit rate for match memory probes, and error or false alarm rate for each type of lure). The proportion of “old” responses was somewhat higher overall in Experiment 1 than in Experiment 2 (see Figure 3), suggesting that the overall response bias in favor of “new” responses was less pronounced in Experiment 2. As in Experiment 1, we report analyses based on  $d'$  values for the three lure conditions. Discriminability tended to be higher in Experiment 2 than Experiment 1 for the lure conditions tested in both (Types III and IV). In Experiment 2, participants' recognition discriminability was lower for irrelevant-consistent lures based on one change (Type IV;  $M = .95$ ,  $SD = .91$ ) than for irrelevant-inconsistent lures based on one change (Type III;  $M = 1.24$ ,  $SD = .83$ ) and irrelevant-inconsistent lures based on two changes (Type V;  $M = 1.4$ ,  $SD = .83$ ),  $F(2, 72) = 6.42$ ,  $MSE = .30$ ,  $p < .003$ ,  $\eta_p^2 = .15$ . Planned comparisons indicated that  $d'$  was significantly lower for irrelevant-consistent lures based on one change when compared with irrelevant-inconsistent lures based on one change,  $t(36) = 3.32$ ,  $p = .002$ ,  $\eta_p^2 = .09$ , and when compared with irrelevant-inconsistent lures based on two changes,  $t(36) = 2.29$ ,  $p = .03$ ,  $\eta_p^2 = .06$ .

The findings from Experiment 2 clearly favor the schematic assimilation hypothesis over the inhibition hypothesis, as discrim-

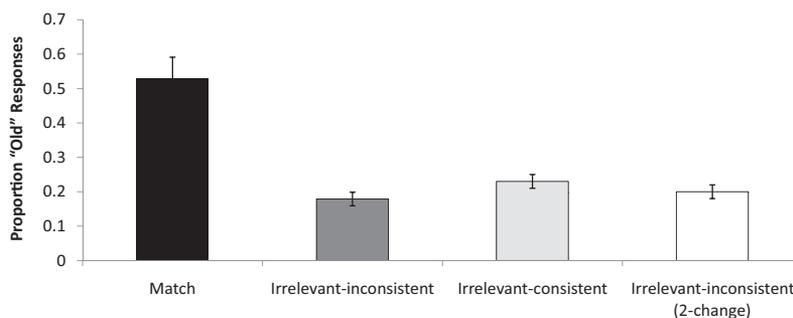


Figure 4. Proportion of “old” responses in Experiment 2. Participants were significantly more likely to falsely endorse irrelevant-consistent lures (Type IV) than either irrelevant-inconsistent (Type III) or irrelevant-inconsistent two-change lures (Type V). (See Figure 2 for examples of all probe types.) Error bars represent standard error of the mean.

inability was just as high for lures that altered the initially inconsistent dimension as for those that altered an initially consistent (although irrelevant) dimension, as long as the change made the A:B relation on that dimension inconsistent with the overall relational schema (i.e., Type V in Figure 2). It appears that higher order relational information inferred during the analogical task was maintained and used in the subsequent recognition task, even though the recognition task probed specific features of the A:B pair, and relations between the A:B and C:D pair were irrelevant to the memory task.

Response times were also significantly different among the lures, such that irrelevant-consistent lures based on one change took significantly longer to correctly reject ( $M = 1,917$  ms,  $SD = 596$ ) than did irrelevant-inconsistent lures based on one change ( $M = 1,782$ ,  $SD = 566$ ) or irrelevant-inconsistent lures based on two changes ( $M = 1,806$  ms,  $SD = 481$ ),  $F(2, 72) = 3.98$ ,  $MSE = 110,382$ ,  $p = .022$ ,  $\eta_p^2 = .09$ . Planned comparisons showed that irrelevant-consistent lures based on one change (Type IV) were significantly slower than either of the other types of lures,  $t(36) > 2.32$ ,  $ps \leq .025$ ,  $\eta_p^2 = .06$ , and that RTs for irrelevant-inconsistent lures based on one change (Type III) and two changes (Type V) were not significantly different,  $t(36) = 0.16$ ,  $p > .87$ ,  $\eta_p^2 = .01$ . The RT pattern across lure conditions thus rules out any possibility of speed-accuracy trade-offs and entirely corroborates conclusions based on the discriminability analyses.

### General Discussion

The present findings reveal that higher order sameness relations, inferred during the course of deciding whether an analogy is valid, guide subsequent recognition decisions for the source analog (A:B pair in a four-term analogy problem). When the recognition task is performed, the relational schema created during the analogical decision task dominates over verbatim memory for perceptual features of the objects, resulting in a loss of discriminability for lures that exhibit a false consistency with the schema established by the relation relevant to the analogy judgment. The observed decrement in discrimination ability for such lures occurred even though the to-be-remembered source (A:B pair in an A:B:C:D proportional analogy) was studied in advance of any knowledge of which dimension would prove to be relevant to the analogy and in full knowledge that a test of veridical memory would follow shortly. Thus, the recognition decrement could not be attributed to failure to initially encode any specific dimension.

The results of Experiment 2 indicate that the recognition decrement was not the result of inhibition making the initially inconsistent dimension less inaccessible. Discriminability was just as high for the inconsistent dimension as for a consistent (although also irrelevant) dimension when the lure was created by altering the feature of both the A and B objects on the inconsistent dimension, thus maintaining the original relation (same or different) on that dimension. Rather, the best overall explanation of the observed pattern of recognition performance is that recognition accuracy was impaired when the lure exhibited a (false) relation that was consistent with the dominant relational organization. As proposed long ago by Bartlett (1932), inconsistent aspects of a situation can be assimilated to a general schema. The present findings suggest that such assimilation can be triggered by analogical reasoning and can result in impairment of the ability to

recognize aspects of a source analog previously encoded into memory.

A possible alternative explanation of our results is that participants did not change their memory representations as a result of the analogical comparison but, rather, in the face of poor memory for the source analog, were biased to accept as same lures that minimized the number of dimensions inconsistent with the dimension relevant for the analogical comparison. However, such a guessing strategy would not be effective, as all of the source analogs actually included exactly one inconsistent relation. Using the terminology of Figure 2, the number of inconsistent dimensions in probes could be zero (Type IV lure), one (Type I or match probes and also Type V lures), or two (lures of Types II and III). If participants had used a guessing strategy based on minimizing the number of inconsistent dimensions in the A:B pair, then they would have responded "old" more often for irrelevant-inconsistent lures (Type IV) than for match probes (Type I). But the opposite difference was obtained in Experiment 1 (see Figure 3).

Alternatively, if participants had used a more optimal guessing strategy based on the actual number of inconsistent dimensions in the A:B pair (one), then they would have responded "old" equally often for match probes (Type I) and irrelevant-inconsistent lures based on two changes (Type V). However, the results of Experiment 2 (see Figure 4) show this was not the case—in both experiments, match probes yielded a reliably higher proportion of "old" responses.

Our findings are consistent with previous work demonstrating that more abstract, relational information is strengthened as a consequence of analogical comparison (e.g., Gentner et al., 2009; Goldstone et al., 1991) and that similarity judgments between two objects can be influenced by information at multiple levels of abstraction (Kroger, Holyoak, & Hummel, 2004; Love, Rouders, & Wisniewski, 1999). The present findings strikingly demonstrate that when a person must decide whether a visual stimulus had literally been seen before, a lure that exhibits a false match in a higher order relation is likely to be mistaken for the original despite mismatches at multiple levels of abstraction. To use the example shown in Figure 2 (irrelevant-consistent, Type IV), the lure was created by altering one feature of the A:B pair: The clothing color of the B figure has been switched from white to black. Thus, relative to the original A:B, the lure has changed (a) a visual feature (white), (b) the first-order relation (different) between the color features of A and B, and (c) the higher order relation (different) between the color relations exhibited by A:B and C:D. All of these discrepancies would support rejecting the lure as "new." However, these discrepancies were often outweighed by the fact that this lure displays a first-order relation (same) that matches the first-order relation of the actual A:B pair on the relevant dimension (width) and hence matches the higher order relation (same) between A:B and C:D on the relevant dimension. That is, the irrelevant-consistent lure is (falsely) consistent with the overall analogical schema defined by the relevant dimension and the two irrelevant dimensions consistent with it.

Current theories of analogical mapping (for a review, see Gentner & Forbus, 2011) provide mechanisms by which analogical mapping can create new relational structure; however, none have directly addressed the question of whether and how prior information about the source could be altered through the process of mapping. On the basis of the present findings, it appears that

people may re-represent the information used to solve the analogy problem. Specifically, the features of objects on a dimension inconsistent with the overall analogical schema may be revised to create a false consistency, and subsequent recognition judgments may be guided by the schema. Our results are consistent with demonstrations of schema-driven distortion of memory but also extend previous findings by showing that memory distortion can occur at a relatively short timescale. In addition, most previous demonstrations of schema-driven distortion have relied on pre-stored knowledge that could influence the encoding and retrieval of new information, whereas in our task, each relational schema was created on the fly for an individual analogy problem.

The precise mechanisms that yield schematic assimilation based on analogical reasoning require more detailed investigation. In particular, it is unclear whether information at the level of specific features of the source analog is actually lost or altered or whether the loss of discriminability is due entirely to regularization of first- and higher order relations, which might occur at the time of the recognition task. Also, in the present experiments, the recognition judgment occurred shortly after the analogical comparison. It is unclear whether the effects reported here would persist or whether after a longer delay the influence of the analogical comparison on memory for the source analog would disappear. A fuller understanding of the mechanisms by which analogical reasoning impacts recognition memory may require more detailed consideration of interactions between multiple brain regions (notably the prefrontal cortex and the hippocampus) that are involved in coordination of reasoning with memory (Knowlton, Morrison, Hummel, & Holyoak, 2012).

Finally, our findings have potential implications for the use of analogies and physical models in teaching. As noted earlier, source analogs that educators consider to be broadly effective (e.g., the factory analog to cellular structure and functions, or the solar system analog to the atom) often include elements that are inconsistent with the intended relational schema for the target domain. Under some circumstances, it seems possible that these mismatching elements may be altered in memory by the very process of analogical reasoning. Reasoning does not only build on information already stored in memory—it may also change it.

## References

- Anderson, M. C., & Spellman, B. A. (1995). On the status of inhibitory mechanisms in cognition: Memory retrieval as a model case. *Psychological Review*, *102*, 68–100. doi:10.1037/0033-295X.102.1.68
- Bartlett, F. C. (1932). *Remembering: A study in experimental and social psychology*. Cambridge, United Kingdom: Cambridge University Press.
- Bäumel, K.-H., Pastötter, B., & Hanslmayr, S. (2010). Binding and inhibition in episodic memory—Cognitive, emotional, and neural processes. *Neuroscience & Biobehavioral Reviews*, *34*, 1047–1054. doi:10.1016/j.neubiorev.2009.04.005
- Blanchette, I., & Dunbar, K. (2002). Representational change and analogy: How analogical inferences alter target representations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*, 672–685. doi:10.1037/0278-7393.28.4.672
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436. doi:10.1163/156856897X00357
- Butler, K. M., Williams, C. C., Zacks, R. T., & Maki, R. H. (2001). A limit on retrieval-induced forgetting. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 1314–1319. doi:10.1037/0278-7393.27.5.1314
- Catrambone, R., & Holyoak, K. J. (1989). Overcoming contextual limitations on problem-solving transfer. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 1147–1156. doi:10.1037/0278-7393.15.6.1147
- Cho, S., Holyoak, K. J., & Cannon, T. D. (2007). Analogical reasoning in working memory: Resources shared among relational integration, interference resolution, and maintenance. *Memory & Cognition*, *35*, 1445–1455. doi:10.3758/BF03193614
- Cho, S., Moody, T. D., Fernandino, L., Mumford, J. A., Poldrack, R. A., Cannon, T. D., . . . Holyoak, K. J. (2010). Common and dissociable prefrontal loci associated with component mechanisms of analogical reasoning. *Cerebral Cortex*, *20*, 524–533. doi:10.1093/cercor/bhp121
- Day, S. B., & Gentner, D. (2007). Nonintentional analogical inference in text comprehension. *Memory & Cognition*, *35*, 39–49. doi:10.3758/BF03195940
- Fischhoff, B. (1982). For those condemned to study the past: Heuristics and biases in hindsight. In D. Kahneman, P. Slovic, & A. Tversky (Eds.), *Judgment under uncertainty: Heuristics and biases* (pp. 335–352). New York, NY: Cambridge University Press. doi:10.1017/CBO9780511809477.024
- Gentner, D. (1983). Structure mapping: A theoretical framework for analogy. *Cognitive Science*, *7*, 155–170. doi:10.1207/s15516709cog0702\_3
- Gentner, D., & Forbus, K. D. (2011). Computational models of analogy. *Wiley Interdisciplinary Reviews: Cognitive Science*, *2*, 266–276. doi:10.1002/wcs.105
- Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 99–129). Hillsdale, NJ: Erlbaum.
- Gentner, D., Loewenstein, J., Thompson, L., & Forbus, K. D. (2009). Reviving inert knowledge: Analogical abstraction supports relational retrieval of past events. *Cognitive Science*, *33*, 1343–1382. doi:10.1111/j.1551-6709.2009.01070.x
- Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology*, *12*, 306–355. doi:10.1016/0010-0285(80)9013-4
- Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology*, *15*, 1–38. doi:10.1016/0010-0285(83)90002-6
- Goethals, G. R., & Reckman, R. F. (1973). The perception of consistency in attitudes. *Journal of Experimental Social Psychology*, *9*, 491–501. doi:10.1016/0022-1031(73)90030-9
- Goldstone, R. L., Medin, D. L., & Gentner, D. (1991). Relational similarity and the nonindependence of features in similarity judgments. *Cognitive Psychology*, *23*, 222–262. doi:10.1016/0010-0285(91)90010-L
- Gómez-Ariza, C. J., Lechuga, M. T., Pelegrina, S., & Bajo, M. T. (2005). Retrieval-induced forgetting in recall and recognition of thematically related and unrelated sentences. *Memory & Cognition*, *33*, 1431–1441.
- Green, A. E., Fugelsang, J. A., & Dunbar, K. N. (2006). Automatic activation of categorical and abstract analogical relations in analogical reasoning. *Memory & Cognition*, *34*, 1414–1421. doi:10.3758/BF03195906
- Hicks, J. L., & Starns, J. J. (2004). Retrieval-induced forgetting occurs in tests of item recognition. *Psychonomic Bulletin & Review*, *11*, 125–130.
- Higgins, E. T., & Liberman, A. (1994). Memory errors from a change of standard: A lack of awareness or of understanding? *Cognitive Psychology*, *27*, 227–258. doi:10.1006/cogp.1994.1017
- Holyoak, K. J. (2012). Analogy and relational reasoning. In K. J. Holyoak & R. G. Morrison (Eds.), *The Oxford handbook of thinking and reasoning* (pp. 234–259). New York, NY: Oxford University Press. doi:10.1093/oxfordhb/9780199734689.001.0001
- Holyoak, K. J., & Koh, K. (1987). Surface and structural similarity in analogical transfer. *Memory & Cognition*, *15*, 332–340. doi:10.3758/BF03197035

- Holyoak, K. J., & Simon, D. (1999). Bidirectional reasoning in decision making by constraint satisfaction. *Journal of Experimental Psychology: General*, *128*, 3–31. doi:10.1037/0096-3445.128.1.3
- Holyoak, K. J., & Thagard, P. (1989). Analogical mapping by constraint satisfaction. *Cognitive Science*, *13*, 295–355. doi:10.1207/s15516709cog1303\_1
- Holyoak, K. J., & Thagard, P. (1995). *Mental leaps: Analogy in creative thought*. Cambridge, MA: MIT Press.
- Knowlton, B. J., Morrison, R. G., Hummel, J. E., & Holyoak, K. J. (2012). A neurocomputational system for relational reasoning. *Trends in Cognitive Sciences*, *16*, 373–381. doi:10.1016/j.tics.2012.06.002
- Kroger, J. K., Holyoak, K. J., & Hummel, J. E. (2004). Varieties of sameness: The impact of relational complexity on perceptual comparisons. *Cognitive Science*, *28*, 335–358.
- Kurtz, K. J., & Loewenstein, J. (2007). Converging on a new role for analogy in problem solving and retrieval: When two problems are better than one. *Memory & Cognition*, *35*, 334–341. doi:10.3758/BF03193454
- Loftus, E. F., & Palmer, J. C. (1974). Reconstruction of automobile destruction: An example of the interaction between language and memory. *Journal of Verbal Learning and Verbal Behavior*, *13*, 585–589. doi:10.1016/S0022-5371(74)80011-3
- Love, B. C., Rouder, J. N., & Wisniewski, E. J. (1999). A structural account of global and local processing. *Cognitive Psychology*, *38*, 291–316. doi:10.1006/cogp.1998.0697
- Markman, A. B. (1997). Constraints on analogical inference. *Cognitive Science*, *21*, 373–418. doi:10.1207/s15516709cog2104\_1
- Markman, A. B., & Gentner, D. (1997). The effects of alignability on memory storage. *Psychological Science*, *8*, 363–367. doi:10.1111/j.1467-9280.1997.tb00426.x
- Morrison, R. G., Holyoak, K. J., & Truong, B. (2001). Working-memory modularity in analogical reasoning. In J. D. Morre & K. Stenning (Eds.), *Proceedings of the Twenty-Third Annual Conference of the Cognitive Science Society* (pp. 663–668). Mahwah, NJ: Erlbaum.
- Perfect, T. J., Moulin, J. A., Conway, M. A., & Perry, E. (2002). Assessing the inhibitory account of retrieval-induced forgetting with implicit memory tests. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*, 1111–1119. doi:10.1037/0278-7393.28.6.1111
- Perrott, D. A., Gentner, D., & Bodenhausen, G. V. (2005). Resistance is futile: The unwitting insertion of analogical inferences in memory. *Psychonomic Bulletin & Review*, *12*, 696–702. doi:10.3758/BF03196760
- Richland, L. E., Morrison, R. G., & Holyoak, K. J. (2006). Children's development of analogical reasoning: Insights from scene analogy problems. *Journal of Experimental Child Psychology*, *94*, 249–273. doi:10.1016/j.jecp.2006.02.002
- Schustack, M. W., & Anderson, J. R. (1979). Effects of analogy to prior knowledge on memory for new information. *Journal of Verbal Learning and Verbal Behavior*, *18*, 565–583. doi:10.1016/S0022-5371(79)90314-1
- Simon, D., & Holyoak, K. J. (2002). Structural dynamics of cognition: From consistency theories to constraint satisfaction. *Personality and Social Psychology Review*, *6*, 283–294. doi:10.1207/S15327957PSPR0604\_03
- Sternberg, R. J. (1977). Component processes in analogical reasoning. *Psychological Review*, *84*, 353–378. doi:10.1037/0033-295X.84.4.353
- Storm, B. C., & Levy, B. J. (2012). A progress report on the inhibitory account of retrieval-induced forgetting. *Memory & Cognition*, *40*, 827–843. doi:10.3758/s13421-012-0211-7
- Verde, M. F., & Perfect, T. J. (2011). Retrieval-induced forgetting in recognition is absent under time pressure. *Psychonomic Bulletin & Review*, *18*, 1166–1171.
- Viskontas, I. V., Morrison, R. G., Holyoak, K. J., Hummel, J. E., & Knowlton, B. J. (2004). Relational integration, inhibition and analogical reasoning in older adults. *Psychology and Aging*, *19*, 581–591. doi:10.1037/0882-7974.19.4.581
- Wixson, D. R., & Laird, J. D. (1976). Awareness and attitude change in the forced-compliance paradigm: The importance of when. *Journal of Personality and Social Psychology*, *34*, 376–384. doi:10.1037/0022-3514.34.3.376

Received June 1, 2013

Revision received January 23, 2014

Accepted January 27, 2014 ■