Re-representation in comparison and similarity

Samuel Day (days@susqu.edu)

Jennifer Asmuth (asmuth@susqu.edu)
Department of Psychology, Susquehanna University
514 University Ave., Selinsgrove, PA 17870 USA

Abstract

Re-representation is a crucial component of structure mapping theory, allowing individuals to notice structural commonalities between situations that do not initially have identical relational representations. Despite its theoretical importance, however, this concept has been the subject of very little empirical work. In two experiments, we find that a case's participation in one comparison systematically changes its perceived similarity to new cases, in a pattern consistent with re-representation. Additional work rules out alternative explanations based on relational priming.

Keywords: analogy; re-representation; similarity

Introduction

Consider how similar you find the following events:

- *Nicole finally got out of the bad relationship that had prevented her from pursuing her own interests.*
- *As the zoo keeper was busy cleaning its habitat, the Burmese python was able to escape its open cage.*

If you are like the participants in our research, you were probably willing to call these events fairly similar, at least after a little bit of consideration. In a very literal sense, these cases differ in significant ways—in their settings, their characters, their implications, even in the species of their protagonists. At a more abstract level, however, they share important structural features. Specifically, both situations describe characters who are able to escape from a confining environment.

The dominant model for understanding structured comparisons such as these is Gentner's (1983, 1989) *structure mapping theory* (SMT). According to this model, individual cases involve hierarchically-structured mental representations of labeled relations, each of which may take other relations or entities as arguments. For example, the common relational structure in the sentences above might be conveyed through a proposition such as: ESCAPED_FROM(ESCAPER, CONFINING_ENVIRONMENT). In this formulation, ESCAPED_FROM is a *relation*: it describes a relationship between multiple entities, and is therefore represented as a predicate that takes multiple distinct arguments. These arguments represent the assignment of entities to the relation's roles.

Comparison, according to SMT, involves a process of *mapping* in order to establish a *structural alignment* between the representations. The goal of this process is to define *correspondences* between the representations while following certain important rules and constraints. For example, although two corresponding objects may be quite dissimilar (e.g., Nicole and the python), relations in two representations will only be mapped to one another if they are semantically identical. Another constraint, the principle of *one-to-one correspondence*, states that each element in one representation may be mapped to no more than one element in the other. Additionally, if relations in two representations correspond to one another, those relations' arguments must also correspond (the principle of *parallel connectivity*).

In the example cases above, the ESCAPED_FROM relations in the two representations would be placed in correspondence, which is allowed because they are identical. In order to maintain parallel connectivity, the arguments of those relations would then be mapped in a role-consistent way, despite their surface differences: Nicole would correspond with the python (they are both "escapers"), and her bad relationship would correspond with the snake's cage (as the confining environments).

Structure mapping theory has been a very successful model for understanding a wide range of cognitive phenomena, including similarity, analogy, classification and knowledge transfer (see Markman & Gentner, 2001). However, in the basic form described above, it would quickly run into significant problems in the real world. For example, as noted, SMT asserts that relations may only be mapped to one another if they are semantically identical. However, it is not difficult to find cases that are perceived as analogically similar despite having non-identical relations. For example, people can easily recognize the structural similarity between *Bill drove to the store* and *Bill jogged to the store*, even though their relations do not perfectly match (Gentner & Kurtz, 2006). Or consider the sentences *John is taller than George* and *Martha is shorter than Mary*. Despite the conspicuous appropriate mapping (John and Mary are both taller), strict enforcement of the identity requirement would lead to a failed match, since TALLER_THAN and SHORTER_THAN are clearly not the same.

Fortunately, researchers have proposed a way around this problem. Specifically, it is theorized that representations may undergo a process of *re-representation*, in which structural and conceptual changes occur in order to enable potential relational matches (see Falkenhainer, Forbus & Gentner, 1989; Holyoak, Novick & Melz, 1994; Kotovsky & Gentner, 1996; Kurtz, 2005). A variety of methods for re-representation have been proposed. For example, a cognitive system may store information about the similarity of different relations (e.g., knowing that *drive* is relatively similar to *jog*; Holyoak & Thagard, 1989), or may initiate a search for common superordinate relations (e.g., both *drive* and *jog* are examples of *move*; Falkenhainer, et al., 1989). Another approach is to decompose a relation into its component structure (e.g., Gentner, 1983; Gentner & Kurtz, 2006). For example, *buying a book* and *taking a book* do not initially

contain a match, but their relations can be decomposed into representations such as:

- *BUY(book)* → *CAUSE(PAY_FOR(book), OBTAIN(book))*
- *TAKE(book)* → *CAUSE(PICK_UP(book), OBTAIN(book))*

which would reveal an identically-matching predicate: OBTAIN.

Despite the importance of re-representation to the overall theory of structure mapping, however, it has been the subject of very little empirical work. The primary experimental research directly addressing the issue comes from Gentner and Kurtz (2006). Participants in their studies were willing to call two sentences analogous when the verbs were nearly synonymous (*Fred* ***reclined*** *on the couch* and *Carl* ***lay*** *on the couch*) or semantically "near" to one another (*Fred* ***reclined*** *on the couch* and *Carl* ***sat*** *on the couch*), but not when they were semantically "distant" in meaning (*Fred* ***reclined*** *on the couch* and *Carl* ***sneezed*** *on the couch*). Interestingly, response times were significantly longer when judging the "near" verbs than the synonyms. This finding is interpreted as evidence for re-representation, which would have required additional processing in order to determine a match. The authors also reported a tendency for participants to use new language (terms not present in either sentence) in their later justifications for their similarity ratings, consistent with a change in how those cases were represented. They acknowledged, however, that this might have reflected processes occurring during the justification task itself rather than the initial comparison.

In our studies, we use similarity ratings to assess potential re-representation. Similarity is a fundamental psychological process thought to play a role in everything from stimulus generalization in classical conditioning (Pavlov, 1927; Shepard, 1987) to categorization (e.g., Smith & Medin, 1981), retrieval (e.g., Hintzman, 1984), inference (e.g., Osherson, et al., 1990) and problem solving (e.g., Ross, 1987). Similarity ratings have also been used successfully in prior research as a measurement of representational change (e.g., Boroditsky, 2007; Goldstone, Lippa & Shiffrin, 2001). In the present experiments, we examine whether participation in one comparison can alter a case's mental representation in a way that changes its perceived similarity to new cases.

For example, consider the similarity between these cases:

- *While testing a network security system, the computer scientist inadvertently released a destructive virus onto the internet.*
- *As the zoo keeper was busy cleaning its habitat, the Burmese python was able to escape its open cage.*

Participants in our studies were able to recognize important structural commonalities between the described events, and responded with fairly high similarity ratings. In this case, the two situations are similar because they both describe someone inadvertently releasing something dangerous. According to SMT, this perceived similarity would require them to establish a common relational representation for the overlap between the cases, such as re-representing both in terms like: RELEASE(AGENT, RELEASED_ENTITY). But consider what would happen if a participant then compared one of those cases to a new situation, as in:

- *As the zoo keeper was busy cleaning its habitat, the Burmese python was able to escape its open cage.*
- *Nicole finally got out of the bad relationship that had prevented her from pursuing her own interests.*

Now the relational structure of the first sentence, established during the prior comparison, would be incompatible with that of the second, because the RELEASE relation is not identical with the ESCAPE relation. (Of course, this depends on some assumptions about participants' mental representations, but ones that are borne out by our data—see General Discussion.) At this point, it is possible that the participant might devote the additional processing effort required to change the representational structure yet again, in search of potential shared relations. However, in most real-world experiences—as in most experimental settings—we believe that individuals will tend to exert a more modest level of processing, in this case typically relying on the representation that has already been created. If so, they would determine that the two cases in the second comparison are simply not very similar to one another.

In these two experiments, we examine whether similarity ratings are reliably higher when one of the compared cases has recently participated in another comparison that involves the same shared relational structure, relative to recent comparisons involving a different structure. For control purposes, the relevant test comparisons were always the same across participants—only the preceding comparison varied between conditions. In Experiment 1, we establish this basic effect, while Experiment 2 both replicates this finding and rules out alternative explanations based on relational priming.

Experiment 1

Participants Thirty participants were recruited through Amazon's Mechanical Turk in return for $1.00 payment.

Materials and Design The study was computer-based, and was administered online. After reading the instructions, each participant read 18 sentence pairs, presented on-screen one at a time. Participants were asked to rate the similarity of each pair by clicking on a horizontal 15-point scale. Above the scale was a prompt, "How similar are these situations?", and the scale's endpoints were labeled *Very dissimilar* and *Very similar*. The entire task took approximately five minutes to complete.

We developed six *Standard* sentences, each of which could reasonably be construed according to two different relational structures, which we will refer to as *Structure A* and *Structure B* (see Figure 1 for a visual depiction of the overall design). For example, the sentence about the python and the zoo keeper described in the Introduction could be represented as an example of "being able to escape from a confining environment," or as an example of "inadvertently releasing something dangerous." Each of these Standards was involved in two consecutive comparisons.

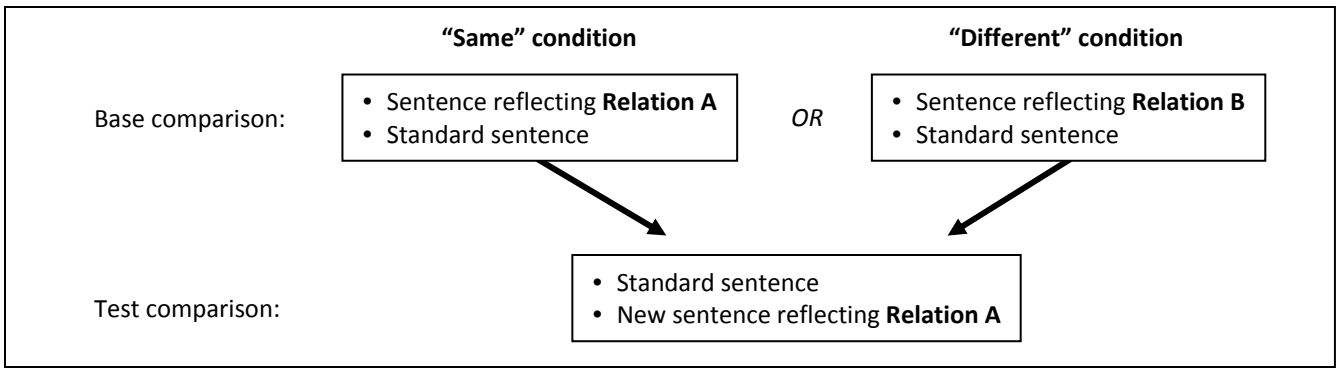

Figure 1: Design of Base-Test comparison pairs in Experiment 1.

We will refer to the first of these comparisons for each Standard as the *Base comparison*. The other sentence in the Base comparison varied between participants: approximately half of the participants compared the Standard to an unambiguous example of Structure A, while the remainder compared the Standard to an example of Structure B. The subsequent trial was the *Test comparison*. The sentences in this comparison were the same for all participants: the Standard was compared to a new example of Structure A. Ratings from the six Test comparisons (one for each Standard) provided the relevant measurement in our experiment. While the sentences in the Test comparisons were identical for all participants, they were classified as either *Same* trials or *Different* trials, according to whether the preceding Base comparison involved the same relational structure (Structure A) or a different structure (Structure B). Our primary question within this experiment is whether similarity ratings on Same trials would be significantly greater than those on Different trials, consistent with re-representation of the Standard.

In sum, the relevant stimuli included six relevant items sets, each containing one Standard sentence, two analogous examples of Structure A (one for potential use in the Base comparison and one for the second Test comparison), and one example of Structure B (for potential use in the Base comparison).

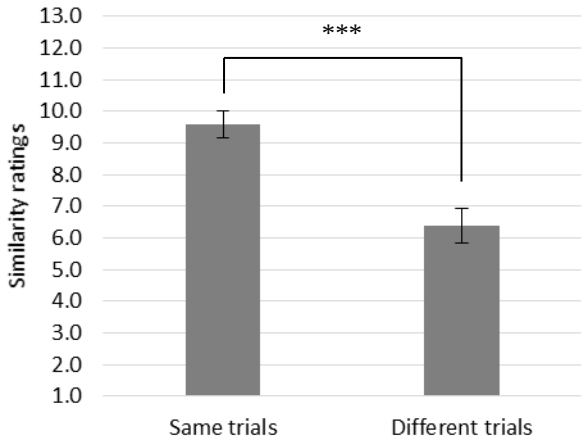

Figure 2: Results from Experiment 1

Each participant completed three Same trials and three Different trials. The condition (Same vs. Different) of each of the six Test trials was assigned randomly for each participant. The presentation order of the six comparison pairs also varied randomly between participants. Additionally, participants completed six filler comparisons—one at the beginning of the task, and one following each of the Test trials except the last—for a total of 18 comparisons.

Results and Discussion A paired-samples t-test revealed a significant difference between conditions (see Figure 2; $t(29) = 4.99$, $p < .001$, $d = 1.17$), with Same trials ($M = 9.59$, $SD = 2.41$) receiving considerably higher similarity ratings than Different trials ($M = 6.40$, $SD = 2.99$). To ensure that these effects were not driven by a small subset of the materials, we also analyzed the data across items. Similarity ratings for all of the six items were higher during Same trials than Different trials, and there was a significant difference between the ratings at the item level ($t(5) = 4.13$, $p = .009$, $d = 2.23$). Because the sentences in these Test trials were identical for all participants, these systematic differences must reflect the influence of the Base comparisons that preceded them, the sole variation between conditions.

The observed pattern is consistent with a process of re-representation. According to this explanation, the structure and content of the mental representation of the Standard sentence was altered during the Base comparison in order to maximize its similarity to its paired sentence. When the resulting representational structure was also a good match for the sentence in the subsequent Test trial, a straightforward mapping would have been possible and comparison would proceed smoothly. However, when the initial re-representation left the Standard with a structure that mismatched the paired sentence in the Test trial, the perceived similarity between the sentences would be poor unless the participant devoted the additional processing effort necessary to alter the Standard yet again.

Experiment 2

Changes in perceived similarity represent a straightforward, low-level means of assessing participants' mental representations. However, while our data is consistent with the proposed explanation of re-representation, there is a salient alternative explanation that must also be considered. Our

approach suggests that the changes in similarity ratings were the result of persisting changes in the mental representations of the Standard sentences themselves. However, our data could also be explained by the activation of more abstract representations that are external to the individual sentences, through a process of relational priming.

Consider the example stimuli discussed in the Introduction, with Nicole escaping from her bad relationship, and the python escaping from its enclosure at the zoo. In the course of comparing these situations, participants may be activating an abstract representation of the relation ESCAPED_FROM. In fact, there is considerable empirical evidence that comparison can promote the generation or activation of abstract knowledge structures (e.g., Catrambone & Holyoak, 1989; Gentner, Loewenstein & Thompson, 2003; Gick & Holyoak, 1983). If so, that representation could presumably still be active and influential during the subsequent Test comparison. As such, it would be in a position to alter the perceived similarity in that trial in at least two different ways. First, it could serve to influence and bias the interpretations of each of the comparison sentences independently. For example, prior research has shown that when individuals are primed with traits such as *brave* and *adventurous*, they tend to develop more positive impressions of a character who attempts dangerous, exciting tasks, relative to participants who were primed with traits such as *reckless* and *foolish* (Higgins et. al, 1977). In other words, the mental availability of a concept appears to bias people's interpretation of novel, ambiguous stimuli. In our example case, priming of a general relational concept such as *escape* could be biasing participants to interpret subsequent sentences as examples of that schema.

At the same time, priming of the ESCAPED_FROM relation could be influencing participants' assessments of the *relationship between* the sentences in the Test trial. A large body of literature has shown that individuals give higher ratings on a variety of measures to a stimulus when it is processed more *fluently* (e.g., Mandler, Nakamura & Van Zandt, 1987; Whittlesea, 1993). This fluency may be the result of a variety of factors, including physical properties of the stimulus itself, but it is most commonly associated with prior exposure to a stimulus. In our study, all participants might have been able to recognize the relevant relationship between the sentences in the Test trials. However, if that particular relationship was already primed and strongly available, the commonalities might have become easier to process, and this ease of processing may in turn have led to a heightened sense of relevance or meaning. If so, prior research suggests that this sense of fluency (or disfluency, in the Different trials) could have influenced participants' similarity ratings in a pattern similar to that observed in our data. Some prior research is consistent with the idea that relational priming may influence comprehension and interpretation (e.g., Estes, 2003; Estes & Jones, 2006).

In some ways, the distinction between an explanation based on re-representation and an explanation based on relational priming is subtle. At a theoretical level, however, this distinction is crucial. As discussed, structure mapping theory is a highly influential model that has had a great deal of explanatory success. However, its viability depends upon its ability to accommodate matches between relationships that are similar but not identical—and *this* ability depends upon the process of re-representation: structural and/or conceptual changes in one or both of the mental representations. An explanation based on relational priming would not require any changes in the representation of the Standard itself, and therefore would provide no evidence that re-representation was occurring. In order to draw any meaningful support for our hypotheses, we therefore need to either rule out a priming explanation, or to demonstrate that re-representation is exerting an influence over and above that of simple priming. In Experiment 2, we add a control condition in order to assess the independent contributions of re-representation.

Participants Sixty participants were recruited through Amazon's Mechanical Turk in return for $1.00 payment.

Materials and Design Experiment 2 included two between-participants conditions. In the *Repeated Standard* condition (n = 30), the materials and procedure were identical to those used in Experiment 1. The *Relational Priming* condition (n = 30), which served as a control, was identical to the Repeated Standard condition with the exception that each of the Standard sentences was compared only once, during the Test trial, rather than in two consecutive trials (the Base and the Test). During the Base trials, participants in this condition were presented with two sentences that were each an example of one of the two relevant relational structures. That is, each participant compared either two examples of Structure A or two examples of Structure B.

For instance, two consecutive trials in the Relational Priming condition might include the following two comparisons:

- *When the instructor turned around to write something on the board, Eric slipped out of the boring lecture.*
- *The rabbit had been cornered by a fox for several minutes, but finally lunged through the weeds and got away safely.*

- *As the zoo keeper was busy cleaning its habitat, the Burmese python was able to escape its open cage.*
- *Nicole finally got out of the bad relationship that had prevented her from pursuing her own interests.*

Unlike Experiment 1, and unlike the Repeated Standard condition in this experiment, participants in this condition did not see the Standard sentence (about the python at the zoo) until the Test comparison. There was therefore no opportunity for prior re-representation of that situation. There was, however, still an opportunity for relational priming. The two sentences in the Base trial are each unambiguous examples of escape, and that is the most salient commonality between them. According to a priming explanation for our data, that relation would have been highlighted and made more accessible during the Base trial, and would therefore be in a position to influence subsequent comparisons.

If the differences in Experiment 1 were solely the result of relational priming, we would expect no differences between the Repeated Standard and Relational Priming conditions, because the priming effects should be equivalent. If, on the other hand, re-

representation is influencing perceived similarity, effects should be greater for participants in the Repeated Standard condition.

Results and Discussion There were three primary goals in Experiment 2. First, it gave us an opportunity to attempt a replication of the findings from Experiment 1, which is important given the novelty of those results. Second, it allowed us to assess whether relational priming may exert an influence in simple consecutive similarity judgments. This is an interesting question in its own right, as we will explore in the General Discussion. Finally, and most importantly, this experiment allowed us to compare the two between-participants conditions, one of which provided the opportunity for re-representation and one of which did not. Because the two conditions should have been equivalent in terms of potential relational priming, any observed advantages for the Repeated Standard condition would provide strong evidence that re-representation had taken place.

We again found an overall advantage for ratings on the Same trials (M = 8.81, SD = 2.49) relative to the Different trials (M = 6.47, SD = 2.36; $F(1, 58) = 46.17$, $p < .001$, $\eta^2_p = .44$). However, because this includes both of the between-participants conditions, we performed a separate analysis of the Repeated Standard condition (which was identical to Experiment 1) to determine whether the basic pattern from the first study had been replicated. This revealed a pattern of results very similar to Experiment 1 (see Figure 3). Similarity ratings for the Same trials (M = 8.89, SD = 2.48) were significantly higher than those for Different trials (M = 5.66, SD = 2.46; $t(29) = 5.72$, $p < .001$, $d = 1.31$), replicating our initial finding. This pattern also held in a separate analysis across items ($t(5) = 7.16$, $p = .001$, $d = 1.94$).

Next, we examined whether relational priming might have had an influence on participants' ratings. In a separate analysis of the Relational Priming condition, Same trials (M = 8.63, SD = 2.53) received higher similarity ratings on average than Different trials (M = 7.28, SD = 1.98), across participants ($t(29) = 3.67$, $p = .001$, $d = 0.59$) and items ($t(5) = 3.00$, $p = .03$, $d = 1.00$), suggesting that relational priming was indeed having a measurable effect.

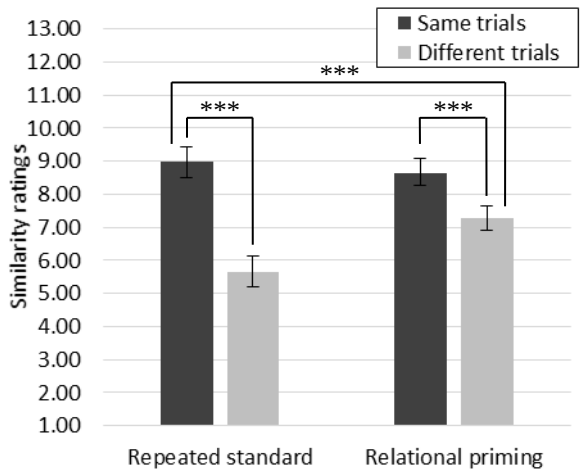

Figure 3: Results from Experiment 2

Most important for our theoretical interests, a 2 (Repeated Standard vs. Relational Priming) × 2 (Same vs. Different trials) ANOVA showed a significant interaction between participant condition and item condition ($F(1, 58) = 8.16$, $p = .006$, $\eta^2_p = .12$). This interaction reflected the fact that the advantage of Same over Different trials was significantly greater in the Repeated Standard condition (mean difference = 3.81, SD = 3.84) than the Relational Priming condition (mean difference = 1.36, SD = 2.03). This advantage was seen for all six items sets individually, and confirmed by an interaction in an analysis across items ($F(1, 10) = 4.08$, $p = .021$, $\eta^2_p = .43$).

(To ensure that the materials were equally apt in both conditions, we confirmed that ratings for the *Base* comparisons did not differ between conditions ($t(59) = 1.22$, $p = .23$). In fact, there was a small numerical advantage for the Relational Priming condition: M = 10.23, SD = 1.52, vs. M = 9.74, SD = 1.55.)

General Discussion

The results of these two studies are informative in several ways. First and foremost, they provide important evidence for a process of re-representation during comparison. As the dominant model of analogy and structured comparison, structure mapping theory has been used to explore and explain a wide variety of cognitive phenomena. However, its ability to scale up to even very basic real-world situations depends on its ability to flexibly find connections between related but non-identical structures. Re-representation has historically been cited as the underlying explanation for this ability. Despite its theoretical importance, however, direct evidence for re-representation has remained scarce. In our studies, comparing a standard case to one situation systematically changed its perceived similarity to new cases. The pattern of these changes indicates that the representational structure and content of the original standard had been altered in a way that made it more compatible with its compared situation—in other words, it had been re-represented. This effect held even when controlling for potential relational priming effects. By adding support to this critical but under-explored area, our results are able to further bolster the viability of structure mapping theory in general.

Although it was not our primary research focus, another informative contribution of these studies is that Experiment 2 demonstrates a novel form of relational priming. The idea of relational priming—that processing a particular semantic relation in one situation may make it easier to process in the future—seems reasonable, and perhaps even obvious given what we know about priming in other contexts. However, finding evidence to support this phenomenon has not always been straightforward. In one of the earliest experimental attempts, Spellman and colleagues (2001) found no indication of relational priming between word pairs in a lexical decision task, even when participants were explicitly told to focus on the relationships between the presented words. Only when individuals were told to notice that consecutive trials might involve the same relationship was a modest effect observed. Subsequent research has been more successful in finding examples of relational priming, through the use of more tightly controlled stimuli and by having participants engage in tasks that more naturally

involved the activation of relations, such as the interpretation of two-word phrases (e.g., Bendig & Holyoak, 2009; Estes, 2003; Estes & Jones, 2006; Gagné, 2001). However, our control condition in Experiment 2 is the first example to our knowledge that demonstrates relational priming through changes in perceived similarity, and the first to find large effects with such naturalistic stimuli.

Finally, our experiments introduce a novel method for assessing mental representation more generally. As with most studies of this type, the stimuli for the present experiments were coded by the authors largely as a function of our intuitions about the semantics of the situations involved. However, as history has repeatedly shown, researcher intuitions can often be wrong. Furthermore, intuitions can vary markedly between individuals. Consider the following two situations: (1) X was victorious over Y, and (2) Y was defeated by X. In our stimuli, we assumed that these reflected two distinct representational structures. Another researcher, however, might reasonably argue that they are simply two different ways of expressing the same underlying proposition. Our experimental method provides a direct way to address this issue. In our studies, comparing a sentence to a clear example of the DEFEAT structure made it subsequently seem significantly less similar to an unambiguous example of VICTORY. In this case, the intuition that these reflect distinct mental representations appears to have been correct, although until that point it was an open empirical question. Examination of the similarity changes resulting from re-representation offers us an intriguing tool for exploring and answering questions about the semantics of mental relations, and therefore provides a potential window into a variety of important mental processes.

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