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Shaping Relations:
The Effects of Visuospatial Priming on Structured Thought

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

in

Cognitive and Information Sciences

by

Katherine Anne Livins

Committee in charge:

Professor David C. Noelle, Chair

Professor Rick Dale

Professor Leonidas A.A. Doulas

2015

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2015

Dedication

Wander, the road is your footsteps, nothing else;
Wanderer, there is no path,
you lay down a path in walking.
~Machado~

Here's to a long winding path.
Thank you to those who helped me walk it.

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Bibliographical Notice

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Livins, K.A., Spivey, M.J., & Doumas, L.A.A. (2015). Varying variation: the effects of within- versus across-feature differences on relational category learning. *Frontiers in Psychology: Cognition*, 6(29).

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Abstract

While relational reasoning has been described as a process at the heart of human cognition, the degree to which relations may be primed remains an open debate. The current project, entitled *Shaping Relations: The Effects of Visuospatial Priming on Structured Thought* by Katherine Anne Livins wrestles with this debate as part of a PhD dissertation submitted to the University of California Merced in the year 2015 under the oversight of Dr. David C. Noelle.

The project focuses on three questions in hopes of illuminating the debate: 1) is relational priming possible, 2) to what extent is relational priming possible, and, if relational priming is possible, 3) what are the mechanisms by which it functions? The project proceeds to evaluate the current literature, and to argue that relational priming seems possible in the broad sense, but that further research must be completed in order determine its extent and mechanisms. Visuospatial priming is argued to be potentially useful for determining the answers to those questions.

The dissertation presents this analysis based on past findings and then describes the results of a series of four new experiments. The first two experiments establish that visuospatial priming can have an effect on relational reasoning; the third shows that attention might be particularly important for those effects; and the fourth confirms that this is the case. It is ultimately argued that relational reasoning is possible, and that it can occur reasonably automatically, but that its efficacy may rely on the prime's ability to capture and direct attention.

Chapter 1

Introduction

Humans have the ability to notice and exploit commonalities between seemingly dissimilar objects. For instance, one can appreciate that Rutherford's atomic model is somehow like the solar system, in the same way that one can appreciate that a group of people might somehow be like peas in a pod. Like many analogies and schemas, we understand these examples by focusing on their internal relationships, and by appreciating the role-based commonalities within them. So, an electron is related to an atomic nucleus by a rotational relationship in the same way that a planet revolves around the sun. Similarly, people might be squeezed into a small space like an elevator in the same way that peas are squeezed into a pod.

Such comparisons rely on *relational representations*, which can be thought of as logical functions that act on ordered k-tuples (Gentner, 1989). So, if one is told that "a zombie is chasing Alex", then one must appreciate that this relationship has two objects (a zombie and Alex), and that the zombie is the "chaser", while Alex is the "chased" thing. One must also appreciate the order in which these elements are combined, since it can affect the statement's meaning ("Alex chases a zombie" would have a very different meaning, and would likely imply that Alex is having a better, albeit still strange, day).

Reasoning about relations typically involves seeing a "sameness" between objects based on shared roles, while potentially ignoring their features/properties (Holyoak, Gentner, & Kokinov, 2001). For example relationally comparing "the zombie chases Alex" to "Chelsea chases a zombie" would involve aligning the first zombie with Chelsea based on both being "chasers", rather than with the second zombie despite both being zombies. Such comparisons can be difficult (Gentner & Medina, 1998; Dumas & Hummel, 2010) and can significantly tax working memory (Dumas, Hummel, & Sandhofer, 2008; Viskontas et al., 2004; Cho, Holyoak, & Cannon, 2007). It is perhaps unsurprising then that feature-based reasoning seems to be the human default (Gentner, 1988; Waltz et al., 2000) and people often fail to reason relationally unless they are explicitly directed to do so (Gick & Holyoak, 1980, 1983).

That said, people *like* relational comparisons. For example, Gentner (1988) found that adults generally prefer relational comparisons to featural ones, and judge them to be more meaningful. Relations are also pervasive. Some have argued that relational thought is not only "at the core of cognition" (Hofstadter, 2001), but that it is also the thing that makes human cognition unique (Penn, Holyoak, & Povinelli, 2008). While such claims are admittedly controversial, there is good evidence to suggest that it is at least important for a range of processes including analogy-making (Gentner, 1983; Dumas & Hummel, 2005), inductive generalization (Hummel & Holyoak, 2003), linguistic processing (Gentner & Namy, 2006) and even some forms of social cognition (Spellman & Holyoak, 1992). As a result, there has been field-wide interest into how relational cognition functions and how relations may be represented in a cognitive system (e.g., Falkenhainer, & Gentner, 1986; Hummel & Holyoak, 2003; Dumas et al., 2008).

Thus, we are left with the realization that relational reasoning can be difficult to elicit and yet it is desirable. Naturally, this raises the question of how relational reasoning might be encouraged, and how its trajectory might be affected. I argue that the answer may be fruitfully explored by thinking about *priming*.

Broadly speaking, priming can be thought of as a process wherein (typically non-explicit) exposure to a piece of information facilitates later use of that information or of a related concept (e.g., see Schunn & Dunbar, 1996). In other words, at some basic level it is a process by which a cognitive process can be caused or shaped, and so it offers the opportunity to study *how* that shaping takes place. This broad definition will be used throughout this dissertation. *Relational priming* can be thought about in a similar way—i.e., as any process by which relational performance may be promoted, altered, or quickened through exposure to information that is not explicitly connected to a given relational task. Likewise, it offers the same opportunity for thinking about the mechanisms by which the priming occurs, and so the mechanisms by which relational reasoning may be encouraged.

By this definition, a reasonably extensive amount of prior work has already focused on relational priming. For example, some researchers have tried to alter the course of relational mappings and judgments (e.g., Spellman, Holyoak, & Morrison, 2001; Green et al., 2007), while others have tried to promote the recognition of specific relations across different problems (e.g., Schunn & Dunbar, 1996; Kokinov, 1990). However, this body of work has shown mixed results, and there has been little agreement on either the efficacy or the mechanisms by which relational priming might work (e.g., Spellman, et al., 1996; Bassock Pedigo, & Oskarsson, 2008; Schunn & Dunbar, 1996; Green, Spellman, Dusek, Eichenbaum, & Levy, 2001; Pedone, Hummel, & Holyoak, 2001; Leech, Mareschal, & Cooper, 2008; French 2008). In other words, the field is interested in relational priming but does not agree on what to say about it.

A priori, there are at least three broad questions that can be asked about relational priming. First, most simply, *is it possible at all?* Second, *to what extent is it possible?* (For example, how difficult is it to achieve, and what sorts of relational tasks can it affect?) And third, *how might it work?* I will aim to address each of these questions in turn with the ultimate goal of shedding light on how relational priming works, and how it can contribute to the field's understanding of relational reasoning in general.

Thus, this dissertation begins with an overview of the relevant literature. I suggest that the answer to Question 1 is that relational priming is possible, in a broad sense. However, I argue that because Question 3 remains unanswered that the answer to Question 2 remains unclear. To address this problem, I suggest that relational cognition might be primed either by activating content-directed cues (i.e., by using cues that target a relation's representational content) or by directing attention around a problem space (i.e., by using cues that target what part of a relation one attends to and when). I mobilize research from the embodied cognition literature to suggest that sensory-motor cues, specifically visuospatial ones, might be particularly useful for exploring both mechanisms, thereby shedding light on all the above-listed questions.

The experimental portion of this project proceeds as follows: First, because of the disagreement in the literature, and because visuospatial priming has yet to be explored with regard to relational cognition, I present the work published in Livins, Dumas, and Spivey (in press) to establish that sensory-motor priming is capable of affecting relational reasoning. I begin this step by showing that priming affects simple, obviously spatial relations (Chapter 3), before showing that it also affects more complex and abstract relations (Chapter 4). I then pit content-based priming against attentional priming, and show that attention-based priming may be particularly important for the effects seen in

the previous steps of this project (Chapter 5). Finally, I present the work found in Livins, Spivey and Doumas (2015) to show that attention-based manipulations can alter the course of relational recognition in order to show how early in the reasoning process these manipulations can take effect (Chapter 6).

Ultimately, I argue that relational priming is not only possible, but that it can affect a wide range of relations and relational tasks. I also argue that the experimental results presented in this dissertation suggest that priming occurs reasonably automatically and that attention may be an important factor for the priming process. This argument is ultimately used to comment on the mechanisms involved in relational reasoning in a broader sense.

Chapter 2

What We Know

The previous chapter stated that there are three questions that might be asked about relational priming: 1) Can it occur? 2) To what extent can it occur? 3) And by which mechanisms can it occur? This chapter will outline what is already known about relational reasoning and priming, as it can be applied to answering these questions. It will then suggest that, while Question 1 has been answered rather definitively, Questions 2 and 3 require further experimental work. Ultimately, it will argue that Embodied Cognition research might be particularly useful for developing such work because it provides a unique opportunity to subtly prime relations in different ways.

Relational Priming: Is It A Thing?

Before one can ask about priming mechanisms, one must know whether priming is possible at all. Likewise, before one can know whether it is possible to prime something, one must know what one is priming. In the case of relational priming, this means understanding the component parts of relational reasoning.

Relational reasoning, in general, and analogy making, specifically (a sub-type of relational-reasoning), have been broken down into a set of component processes (Holyoak et al., 2001). Specifically, *access* involves retrieving a source analog from long-term memory given a particular target (Hummel & Holyoak, 1997), *mapping* involves finding structural correspondences between that source and target (Hummel & Holyoak, 1997), *transfer* allows that mapping to be used to draw inferences by applying information about the base analog to the target, (Spellman & Holyoak, 1996), and *evaluation* involves adapting those inferences for the constraints and requirements of the problem at hand (Holyoak et al., 2001). Two other steps may even be added to this list: relational *recognition* has been argued to be a necessary first step (Livins & Doumas, 2014), and *learning* has been argued to be an optional final step in which new information, categories, and schemas may be added to memory based on the completed problem (Holyoak et al., 2001).

Studies relevant to relational priming have often been described in terms of which stage of reasoning the given method targeted. Experiments targeting access have been particularly common. For instance, Wharton, Holyoak, Downing, Lange, Wickens, and Melz (1994) used an incidental-learning paradigm to study the degree to which structural similarities could be used to remind someone of an earlier stimulus—in other words, whether structural similarities could increase the probability that participants accessed a memory of an earlier stimulus. They had participants read stories with various forms of content and structure, then take a break before reading more stories. Participants were asked to note any of the previous texts that the new passages reminded them of, and it was found that participants often noted stories with structural consistencies. As a result, Wharton et al. (1994) argued that structural similarities could remind someone of non-present content, and therefore affect access.

Likewise, Schunn and Dunbar (1996) gave participants problems over two days to test whether the content of one problem could influence the solving of another. On the

first day, participants in a priming condition received a biochemistry problem that involved inhibition, while those in a control condition received a biochemistry problem with a different theme. A day later, all participants received a molecular genetics problem that involved inhibition. It was expected that if relational priming took place, then those in the priming condition should have performed better on the second day problem because of the previous exposure to the problem content. Indeed, this was the result and Schunn and Dunbar argued that it suggested that priming could help participants access knowledge for the purposes of problem solving.

Other studies have shown similar findings: Kokinov (1990) found that participants could be primed to solve a difficult relational problem involving an immersion relationship with prior exposure to a structurally similar one, and Holyoak and Koh (1987) showed that such exposure can have effects several days later, even across different reasoning contexts. Furthermore, these studies only represent a subset of the relational priming literature (also see, Gentner, Rattermann, & Forbus, 1993; Green, Fugelsang, & Dunbar, 2006; Blanchette & Dunbar, 2002), and so it seems reasonable to believe that relational priming is a real phenomenon with significant cognitive consequences. However, it is important to note that the literature discussed thus far fails to discuss the limits of these consequences, or how easy/difficult the effects are to achieve—in other words, it does not answer Question 2. Some research has spoken to the issue though; as a result, the next section of this chapter will be dedicated to this research.

Relational Priming: How Much, How Easy?

Question 2, which seeks to specify the limits of relational priming, is more difficult to answer than Question 1 because it requires more than a simple affirmative or negative response. Furthermore, while a number of studies have tried to directly answer Question 1, only a limited number of studies have even attempted to address Question 2.

Spellman, Holyoak and Morrison (2001) conducted one of the few studies that attempted to deal with this topic directly. They used a lexical decision task that required participants to view pairs of letter strings, before deciding whether the strings were English words or not. String pairs were occasionally presented in pairs of items that exemplified a given relation (e.g., “bird” and “nest” are typically associated through a “lives-in” relationship) while later word pairs could exemplify the same relations embodied in those earlier relational pairs (e.g., “bear” and “den”, which also typically exemplify the “lives-in” relation). It was expected that if relations can be primed, then participants should have been faster to classify later word pairs exemplifying a previously seen relationship; however, a priming effect only occurred when participants were explicitly told to pay attention, not only to the relationship between the words within each pair, but also to the relationships between pairs. Spellman et al. (2006) argued that this result indicated that relational priming may be possible, but that it is rare and requires explicit instruction and an ideal context.

Interestingly, other work has directly contradicted this study by finding cases in which priming appeared to work reasonably automatically. For example, Bassok et al. (2008) explored the relationship between semantic and arithmetic relations and found evidence to suggest there is an obligatory activation of addition facts when the problems are paired with semantically aligned word pairs. In one experiment, they showed

participants pairs of words that could be semantically aligned or misaligned, along with number pairs. Both were displayed with a “plus” sign between them, and it was expected that if two words were semantically related (e.g., “tulips-daises”, which additively create “flowers”) they could prime addition facts (e.g., $2+6=8$) because they can be semantically combined. This was the result, as Bassok et al. expected. They argued that their findings relied on implicit priming that did not involve explicit instructions (as were required in the study performed by Spellman et al. 2001), and so the priming must have occurred automatically. Day and Gentner (2007) found a similar automatic priming effect when participants were asked to comprehend and interpret text. In this case, it was found that participants often applied earlier experienced relational content to later examples, yet reported no awareness of making a connection between the two. It was argued that this result suggested an automatic priming process (also see Green et al., 2006 for a similar finding involving analogical judgments).

Bassok et al. (2008) suggested that the difference in observed effects might be the result of methodological differences (i.e., experiments use different relations, different experimental paradigms, different instructions, etc.). This is a reasonable insight, especially given that some studies have shown that context may result in relational priming. For example, McKoon and Ratcliff (1995) used a lexical decision and naming task to show that responses could be shaped by the “relational context” in which they were presented (i.e., by whether words were presented with other words that exhibited a similar relation). However, no conclusive explanation has been provided, and the methodology explanation is simply a possibility at this point. Furthermore, it does not provide an explanation of *why* the primes might be sensitive to context and task-based factors because it does not describe *how* relational priming might work at a functional level. That said, there are models of relational reasoning that make strong predictions that might be used for this purpose. They will be outlined in the next section of this chapter.

Relational Priming: How Might It Work?

Most will agree that humans are capable of thinking about relations, however their representational structure and the functional explanations of their processing have been controversial. At least three schools of thought have developed on the topic, each of which has produced different theories. This section will briefly discuss each approach, as well as the types of models that have instantiated them and how they might account for relational priming.

The earliest theories of relational reasoning argued that relational representations must be “*structured*”, which is to say that they must involve a basic set of representational elements that can be combined to create new, more complex information structures. (It is for this reason that they are sometimes called “*compositional*”.) In general, structured representations were argued to be abstract and discrete—in other words, not tied to specific objects, enduring, and able to be treated as wholes (Markman & Dietrich, 2000). Accordingly, representing “chasing” might involve simply having a representation of “chasing” somewhere in a given system. Thus, according to these accounts, any system that implements relations would be capable of forming an open-ended set of relational statements with a finite vocabulary of predicates (i.e., explicit entities that can take arguments) and objects (i.e., things that can be those arguments)

(Doumas et al., 2008; Peirce, 1897, 1903).

While there are a number of models that implement relations as structured representations, Gentner's Structure-Mapping Theory (SMT) of analogy (a type of relational reasoning; Gentner 1983) is perhaps one of the most famous. It suggested that analogy is primarily guided by structural constraints (i.e., the shared structural relationship between the base and the target; Gentner, 1983, 1989), with semantics (i.e., feature-based similarities) taking a significantly lesser role. It is perhaps unsurprising then that the computational model built to instantiate the theory, the Structure-Mapping Engine (SME) (Falkenhainer, Forbus, & Gentner, 1986, 1989), predicted that human knowledge is most fruitfully conceptualized as a set of propositional networks and that relations are predicates within those networks. In other words, it holds that relational representation is very much like predicate calculus, and that relations are symbolic structures as they were defined above.

Interestingly though, Gentner recognized that this model did not account for what she called "analogical reminding"—a process in which one problem spontaneously reminds someone of a similar problem. While reminding does not seem to be synonymous with priming (because it is the process by which an explicit comparison between two analogs occurs, while prime can involve subtle and non-explicit cues), the two are often discussed in the same contexts (e.g., Schunn & Dunbar, 1996). As a result, Gentner's account of reminding might be used to formulate an understanding of how she and her model might account for relational priming.

Gentner approached reminding experimentally. For example Gentner and Landers (1985) used a paradigm similar to Wharton et al. (1994) where participants read a series of scenarios, took a long break, then read more scenarios and stated which previously-read scenarios the current ones reminded them of. It was found that feature-based reminders were more common, and more easily produced than structure-based ones. As a result, they argued that reminding makes access more likely when it exploits semantically-based similarities instead of structural ones.

Gentner and her collaborators ultimately proposed a two-step reminding process: a retrieval/access stage that initially used nonstructural matching to find relevant analogs, and a mapping stage that relied almost entirely on structural constraints (Forbus, Gentner, & Law, 1994). This account was instantiated in another computational system called MAC/FAC (Forbus et al., 1994): First, Many Are Called (MAC) uses similarity-based retrieval to probe for candidate analogs, before Few Are Chosen (FAC) uses a variation of SME to process those candidates into structured representations and look for one-to-one alignments to create between-analog mappings (Forbus et al., 1994). The model then proposes that access is *semantically* or *content* driven, while mapping is *structure* driven. It was proposed that reminding can occur in the semantically-driven access stage, and then get "approved" by the structurally-driven mapping state.

While symbolic models are extremely powerful and excellent for completing complex analogical mappings, many critics have pointed out that they often struggle to offer a developmental explanation (e.g. Leech, et al., 2008; O'Reilly, Busby, & Soto, 2003). For instance, imagine a model that has a representation like "*collides*", represented as a whole structure (like it is in SME). It seems difficult to imagine how a child might learn that symbolic representation in the first place. Thus, while they might be capable of explaining elements of relational priming, they may not be ideal for explaining relational

reasoning as a whole.

Consequently, some have argued that relations may not actually involve formal structure at all, and that they might be represented *sub-symbolically*. Sub-symbolic representations are representations that carry information in a distributed way. This approach is supposed to mimic neuronal functioning (Markman, 1999; Rumelhart, 1989; Hinton, 1989)—individual cells that, on their own, do not produce intelligent behavior, but when acting in concert are capable of producing all the complexities of human cognition.

This account does not make use of discrete meaningful representational elements that can enter into bound compositions to create new representations. Instead, holistic representations are, by definition, non-decomposable in that they cannot be broken down into meaningful subcomponents. Instead, the system can code a number of representations with the same basic elements by using them in different patterns—like a television uses the same pixels to code for different images. The result is that representations exist only at the level of the entire system and so the interesting work (e.g., the combination of elements) is supposed to be done at a level below the symbols themselves (Chalmers, 1992).

A few relational models have attempted to instantiate these representations, and have relied heavily on relational priming for their efforts. For instance, Leech, Mareschal, and Cooper (2008) suggested that relations are represented as associations in a simple recurrent connectionist network. According to this model, given specific objects as input, context objects prime particular association states that allow the model to produce transformed outputs. For example, imagine the system is asked to complete an “*a* is to *b* as *c* is to *d*” analogy task: exposure to a concept like “puppy” in the context of “dog” might prime a semantic relation like “offspring” so that when “kitten” is presented “cat” will be produced. By this account, relational cognition is not structure-based, but entirely the result of semantic priming.

This account bypasses some of the problems associated with the symbolic accounts—namely, it does not have to deal with the problem of learning structured representations of relations because it does not include structured representations at all. However, it has been widely criticized for being unable to account for the types of behavior that are characteristic of both child and adult relational reasoning. For example, Doumas and Richland (2008) point out that because the model has no way of temporarily binding objects to relational roles, that it would struggle to integrate multiple relations at a time. That is, it is unclear how the model would deal with mapping *chases*(*x*,*y*) and *chases*(*y*,*z*) to *follows*(*a*,*b*) and *follows*(*c*,*a*), even though humans over the age of five routinely solve these sorts of problems (e.g., Richland, Morrison, & Holyoak, 2006). Likewise, French (2008), and Holyoak and Hummel (2008) point out that adult humans often make far-reaching analogies across novel analogs that share few semantic characteristics. For example, most humans are capable of grasping the way in which electrons are like planets, even if it is a novel mapping and one knows little about planetary rotation. In other words, one can appreciate the mapping without possessing an existing association. However, such a mapping would be beyond the model’s capabilities due to its reliance on heavy training.

Thus, yet another representational account was needed, and pluralist approaches were developed to fill it. Generally, pluralism is the idea that multiple types of representations

might be needed to account for human cognition (Markman, 1999; Dove, 2009). When used to account for relational representations, it suggests that relations might need to have symbol-like structure sensitivity, but also be coded in some distributed way.

Symbolic-connectionism is one computational approach that has embodied a pluralist perspective, being defined as “any cognitive architecture that codes relational structures by dynamically binding distributed representations of roles to distributed representations of their fillers” (Holyoak & Hummel, 2003, 221). These models can have the neurally plausible, flexible representations allowed by connectionist designs, and yet modify them to allow for structure by introducing some binding mechanism.

For instance, DORA, a model proposed by Doumas, Hummel and Sandhofer (2008), suggests that structured representations of relations are learned from unstructured feature vectors, and are eventually realized (at least in part) by sets of feature nodes firing in particular temporal patterns. Specifically, DORA (and its predecessor LISA; Hummel & Holyoak, 1997, 2003) posits that relational representations are coded across layers of nodes. In the bottom layer a set of distributed features encode objects and relational roles in a distributed fashion. One layer up, localist nodes combine sets of these features to represent particular objects and relational roles. Those roles are then temporarily bound to objects to create more complex relational structures. For example, features such as “movement”, “horizontal” and “urgency”, may combine to represent *chaser*, while “movement”, “fear” and “ahead” may combine to create *chased*; *chaser* and *chased* may then be bound to objects such as “John” and “Mary” (i.e., *chaser*(John) + *chased*(Mary)), which may ultimately combine to create a propositional structure such as “John chases Mary” (or, *chases*(John, Mary)) (see Figure 1).

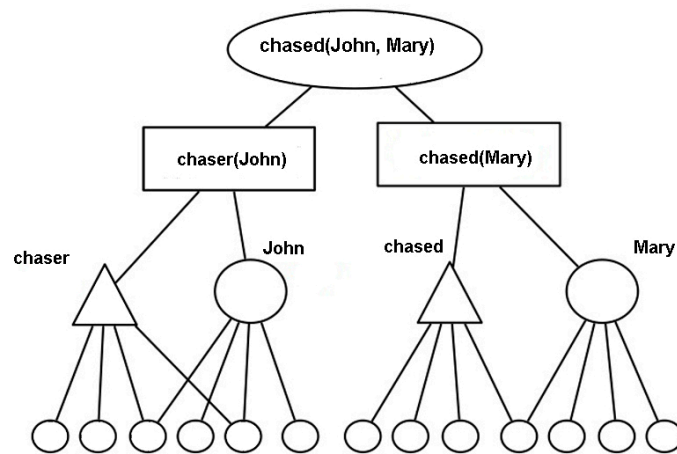


Figure 1: An example of how DORA (Doumas, Hummel, & Sandhofer, 2008) represents relational structures.

It is important to notice that the independence of representational elements and their binding mechanism is at the heart of this type of model (see Doumas et al., 2008; Hummel, 2010). Very simply, a binding mechanism is the way in which a system keeps track of things that go together and separates things that do not. To say that this

mechanism is independent from a system's representational elements means that it cannot be part of the elements themselves. For instance, the elements “long-haired” and “cat”, and “short-haired” and “dog” might be bound to form the propositions *long-haired*(cat) and *short-haired*(dog). However, while the statement *long-haired*(cat) has meaning (a cat that has the property of having long hair) the elements “long-hair” and “cat” should remain independent representations when so bound. This independence ensures that the predicate “long-hair” can mean the same thing whether it is bound to ‘cat’, ‘dog’, or ‘automobile’.

The binding mechanism is also dynamic. That is, it allows bindings that can be created and destroyed on the fly. For instance, if the cat in the above example were to suddenly get a short hair-cut, then the binding of “long-haired” and “cat” would need to be broken, and the very-same representation of “cat” would need to be bound to the “short-haired” predicate to form *short-haired*(cat). In other words, the representation would need to be promiscuous (see Hummel, 2010), such that a single representation could potentially take any argument while still maintaining its meaning. So, “short-haired” should be represented in a way that it can be applied to cats, dogs, people, or sasquatches, and yet still mean the exactly the same thing.

Ultimately, symbolic-connectionist models like DORA account for a wide range of phenomena from both developmental and adult cognition (see e.g., Doumas & Hummel, 2010, 2013; Doumas et al., 2008; Hummel & Holyoak, 1997, 2003; Lim, Doumas, & Sinnett, 2012, 2014; Morrison, Doumas, & Richland, 2011; Sandhofer & Doumas, 2008; Son, Smith, & Goldstone, 2011). They also offer two different avenues for thinking about relational priming: *content-based* priming, and *attention-based* priming.

The former can be explained in terms of how DORA learns relations in the first place. Specifically, early exemplars and experiences are stored as feature-sets in memory, and later information is compared to those memories. As a result, the model suggests that relations are learned by comparing new information to stored information. While DORA does not specify what types of information might end up getting stored (i.e., it does not specify that “lifting” has to be about “verticality”), it does emphasize that relations will inherently have (i.e., be composed of) featural content (which is learned through the experiences that one has in the world). Activating that content can activate the relation, and vice versa. If this account is correct, then relational priming might be a matter of simply activating some subset of a relation's features and allowing that activation to spread.

The later can be explained in terms of how DORA binds. Remember that DORA does not have abstract representations in the same way that traditional symbolic models do. For example, DORA does not have, say, a *chases* node; instead, it is represented by the combination of *chaser* and *chased*, which can be temporarily bound to things like *cat* and *dog* to create something like *chaser*(dog) + *chased*(cat). Importantly, DORA achieves this type of binding through temporal asynchrony—in other words, by tracking when units fire and the sequence in which they do so. So, *chased*(dog, cat) would be represented by firing *chaser*, then dog, then *chased*, then cat, and *chaser* and dog would be bound by firing them in immediate temporal proximity. Thus, the model requires the subsequent firing of each relational role—in most cases, the actor and then the

patient¹. As a result, the model predicts that one must encode both roles (and the objects that fill them) independently in order to encode a relation, and that the order in which things fire is representationally important. Attention may be one way to control the order of this process. Specifically, if attention can change which object is attended to before the other, it may also be able to affect which role fires before the other. If DORA's account is correct, then this change in firing *could* affect which relation is recognized: if one attends to one object playing one role before another object playing another role, then different objects could be bound to different roles and a different relation could be produced.

Ultimately, DORA offers both a plausible explanation of relational reasoning, and two possible mechanisms for relational priming. That said, DORA does not specify the content of those features (just that they exist), nor does it specifically discuss attention (just the role of time in role-filler binding). For instance, while it predicts that *loves* will have some set of features, it does not make claims about what those features are, nor does it *explicitly* outline how attending to the “lover” object before the “beloved” object will affect reasoning. As a result, it does not explicitly account for relational priming.

I argue that creating such an account involves thinking about sensory-motor processing. First, consider where relational features might come from. At a very coarse level the answer must be “the body and its environment”, unless one wants to take a strong nativist stance (e.g., one wants to argue that humans are born with some representation of “chasing”). Likewise, thinking about relations will regularly involve directing attention around one's environment using one's sensory-motor effectors. For example, even the most symbolic task (like applying a mathematical function to a problem) will involve directing attention around a problem space using (at least) one's eyes. As a result, it is reasonable to expect that manipulating sensory-motor and environmental factors could be an effective way of priming relational cognition. The next section of this chapter will provide further justification for this expectation by outlining relevant literature that makes this possibility all the more likely.

Priming With The Body

Embodied cognition has been a growing theoretical framework over the past twenty years. While it was designed to challenge traditional theoretical approaches to Cognitive Science by putting emphasis on the need to consider how cognitive functioning may be affected by the body and the way that one interacts with one's environment (Spivey, 2007; Shapiro, 2001; Wilson, 2002; Varella, Thompson, & Rosch, 1992), it has been used to shed light on a number of cognitive mechanisms (e.g., Barsalou, 1999; Clark, 1997; Lakoff & Johnson, 1999; Meteyard, L., Zokaei, N., Bahrami, B., & Vigliocco, G., 2008; Tucker & Ellis, 2000, 2001, 2004; Zwann & Kaschak, 2009; Zwaan, Madden, Yaxley, Averyard, 2004).

Priming involving the body (especially the type relevant to relational reasoning) has often involved priming movements that are semantically related to a target concept. As a result, it may have implications for exploring and activating relational features. For

¹ Note that DORA can also handle non-directional relations, so the actor does not *have* to fire first. Temporal order simply designates different roles, which include the actor and patient distinctions (Doumas et al., 2008).

example, while there has been little work on relational features in specific, embodied cognition researchers have been looking at the relationship between *image schemas* and verbs for quite some time. Image schemas are generally thought of as primitive structures, which are inherently part of a concept and are derived through culture and worldly interaction (Dodge & Lakoff, 2005; Lakoff & Johnson, 1980; Mandler, 1992). So, *lifting* might have an inherently vertical schema because when one lifts things, it generally involves some sort of vertical movement. If it is the case that a relation has an image schema, then activating some subsection of that schema might be equivalent to activating some subset of that relation's features. As a result, priming might be achieved by activating that schema.

Experimental work in psycholinguistics has shown that image schemas might be perceptually-coded and so activating them might involve visuospatial movement (through vertical or horizontal directionality). For example, Richardson, Spivey, Barsalou and McRae (2003) used both an attention task and a memory-recall task to show that presenting visual stimuli in orientations (vertical or horizontal) that were consistent or inconsistent with the orientation of a verb's meaning affected the speed with which participants completed the task (see also Bergen, Matlock, Lindsay, & Narayanan, 2007). These results suggest that activating visuospatial alignments (or image schemas) can not only affect how people represent action verbs, but also how those verbs are processed in tasks where space is functionally irrelevant (also see Toskos, Hanania, & Hockema, 2004 for a similar effect on verb memorization). While verbs are not synonymous with relations, Richardson et al. used verbs that are inherently relational—each specified an actor and a patient (e.g., *pointed at*, *pushed*, *lifted*, and *argued with*). As a result, these findings suggest that at least some relations may have visuospatial features, and that they can be primed by sensorimotor processes such as visual attention and eye movements.

Other work has exploited similar perceptual and spatial primes to direct attention around a problem space. For example, Pedone et al. (2001) showed that one's ability to solve the Duncker Radiation Problem² (Duncker, 1945) could be impacted, not only by diagrammatic differences in tasks preceding the problem's presentation (e.g., see Gick & Holyoak, 1983), but also by animating those diagrams. For example, they found that an initial task involving animated converging arrows was produced by a greater chance of finding the solution to the problem since it also involves the concept of convergence. They suggested that such animations could alter diagram interpretation and increase the likelihood that it was noticed as a useful source analogue. This may be thought of as automatic priming since the first task was seemingly unrelated to the Duncker Problem, and yet changes in its animation altered success rates.

Grant and Spivey (2003) furthered this work when they found that the problem's solution of converging lasers could also be primed by inducing a converging pattern of

² The Duncker Radiation Problem is a famously difficult insight problem, which involves pretending to be a doctor with a patient who has a tumor in her stomach. As the doctor one can use lasers to destroy the tumor, however it is specified that the power of a given laser will also destroy the patient's skin. The problem is how to destroy the tumor with the lasers without destroying the skin. The answer lays in idea of convergence: many lasers are used at lower powers from different angles, so that the tumor receives the needed amount of intensity, while the intensity that the skin receives is lessened per spot.

attention and eye movements over a diagram of the problem (also see Thomas and Lleras, 2007). Their results suggested that the probability of producing a spontaneous solution (without the use of an explicit analogy) could be affected, not just through symbolic content (e.g., arrows and animations as primes), but also by one's sensory-motor interaction with a diagram corresponding to the problem itself. If eye-movement patterns can prime the visuospatial solution to a famously difficult insight problem, perhaps they can also direct attention around a relational problem space to change the trajectory of the reasoning process.

This collection of research suggests that visuospatial information might be useful for priming relations, either by activating some sort of representational content or by directing attention in some problem-consistent manner. That said, the tasks discussed above were not *inherently* relational enough to demonstrate that visuospatial information can affect the relational reasoning process (i.e., that the activation of such features can have a robust effect on structural tasks). It is important to note that the qualities of relational tasks are contentious (e.g., see Penn et al., 2008), but that existing literature suggests that relational representations must have a number of qualities that can be mapped to a task. Specifically, it has been argued that a relation must be represented explicitly, such that it can take novel arguments to which it is dynamically bound (Doumas et al., 2008; Doumas & Hummel, 2005). These qualities mean that within an experimental context, a reasoner must be able to show that they are reasoning about the roles that objects play rather than object properties, and that those objects (and their properties) can change. For example, crossmapping analogy problems use the same objects in different roles, and require a reasoner to ignore those statistical regularities in favor of role-based properties (e.g., an analogy task involving *chases*(dog, cat) and *chases*(cat, dog) should produce a mapping between the first dog and the second cat, and not between the two dogs). By extension, a relational task should also allow the reasoner to demonstrate flexibility, such that if the objects change (i.e., they are replaced with other objects), that the reasoner can still recognize the relation. Experimentally, this can be demonstrated across trials or exemplars.

Ultimately then, if one considers the existing literature with regard to the efficacy of sensory-motor priming on higher cognition, and one keeps in mind the aforementioned constraints on relational tasks, then it seems possible to design experiments to test the degree to which sensory-motor priming can specifically affect relational cognition. Such designs may help to understand the mechanisms at play with regard to relational priming in general (i.e., whether it might be representation-based or attention-based). Furthermore, because understanding relational priming may comment on why relational reasoning follows a given trajectory at a given time, such designs may also help to specify the mechanisms involved in relational reasoning in broader-sense as well. It is at this point that the next chapter will begin.

Chapter 3

Can Vision and Space Shape Relations?

As stated in the previous chapters, existing work suggests that relational cognition might be shaped by embodied factors, but there is no definitive evidence for it. As a result, this chapter will provide such evidence using empirical methods. Given that this is a somewhat new domain, it will begin modestly. To the point, some relations are more obviously spatial or inspired by sensory-motor processing than others (e.g., “beside” has a tangible relationship with the horizontal axis, while “ameliorates” seems more difficult to tie to some spatial alignment); the current study only used relations of the former type, so it represents only a starting point.

My first experiment employed a pictorial relational category-learning task to determine whether simple, spatial relations can be primed by a subtle visuospatial prime that may capture exogenous attention. It did so by using relationally ambiguous exemplars that simultaneously belonged to two unique relational categories, where learning either category would suffice for successful classification. Visuospatial priming was congruent with one category and incongruent with another, and priming was designed to affect which category was learned.

The task required participants to learn a relational category over the course of multiple exemplars. The exemplars used two-dimensional shapes positioned such that one shape always occluded the other. The categories were defined by the occluding shape’s relative location to the occluded shape on the x- and y-axes (i.e., whether the occluder was to the left or right of the occluded shape, and whether it was above or below the occluded shape). However, it is important to note that while the exemplars involved shapes, the object attributes of those shapes were non-predictive of category membership – only the location of the occluding shape denoted membership.

The fact that the specific shapes were not predictive of category membership means that our paradigm meets the specified criteria for a relational task. Gentner and Kurtz (2005) pointed out that while not all categories are relational, some are. Specifically, relational categories define membership based on some common relational structure instead of the object attributes exhibited by members. For example, *occluders* make up a relational category since they are not defined by their features, but rather by how an object stands in relation to other objects. In other words, relational categories are not dependent on specific objects, but on the roles that objects play; as a result, thinking about them involves using the same cognitive mechanisms as other types of relational cognition. Thus if it is possible to prime category learning on a relational category-learning task, then it seems likely that relational reasoning will be primable in a more general sense.

Participants

Participants were 106 undergraduate students from the University of California, Merced. They were recruited through a participant pool and received course credit for participation. All participants had normal to corrected-to-normal vision. Fourteen of these participants were not included in the final statistical analyses because they failed to solve

the given problem in a meaningful way, however they were used to calculate the sample's overall ability to complete the task.

Categories

As previously mentioned, categories were created using circles and squares and their relative placement on the x- and y-axes. More specifically, every exemplar showed two shapes, where one occluded the other; the specific shapes were selected at random at the beginning of each trial such that each trial could contain two circles, two squares, or one of each, and one shape always occluded the other. A pair of shapes was thought of as an “above” configuration if the occluder was above the occluded shape, a “below” configuration if the occluder was below the occluded shape, a “left-of” configuration if it was to the left, and a “right-of” configuration if it was to the right (see Figure 2).

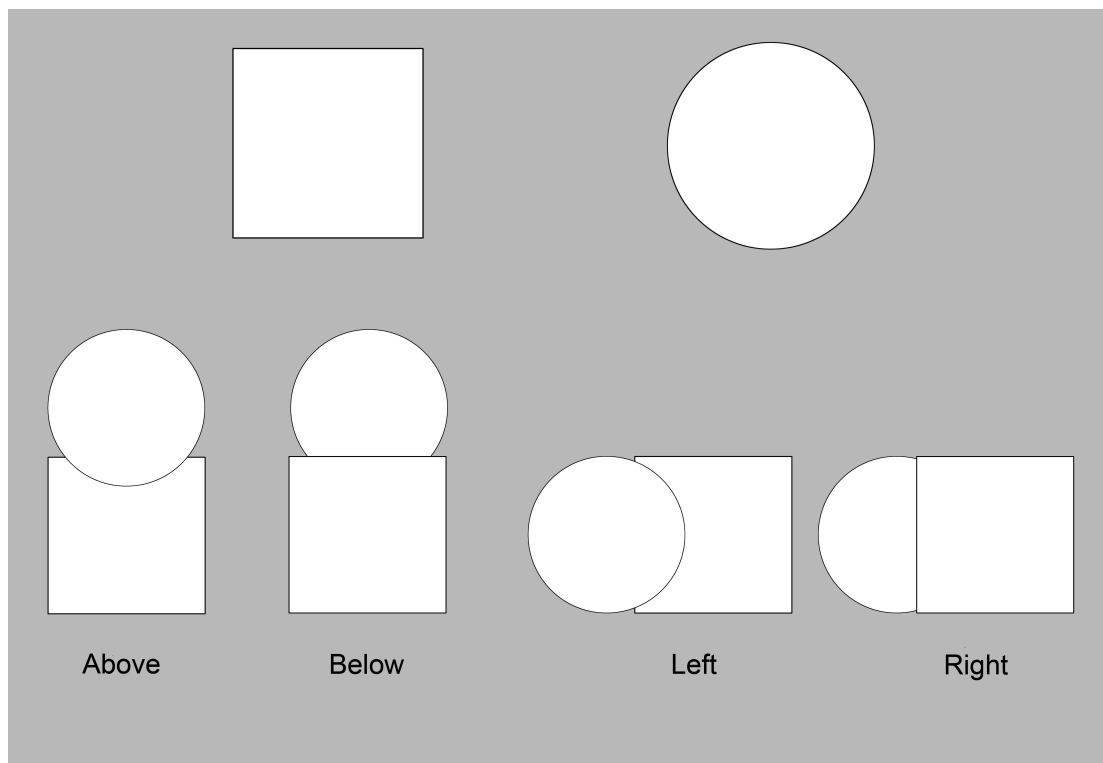


Figure 2: An example of how two shapes could combine to create exemplars that had an occluder take a value on the “left-of/right-of” dimension or the “above/below” dimension. In both case the critical category-defining relationship was the placement of the occluder.

Every shape-pair simultaneously took a value on both the “left-of/right-of” relation and on the “above/below” relation, thus creating relationally ambiguous stimuli. As a result, stimuli could depict an “above/left-of” configuration that depicted an occluder above and to the left of the occluded shape, a “below/right-of” configuration that depicted an occluder to the bottom and to the right of the occluded shape, an “above/right-of”

configuration that depicted an occluder to the top and to the right of the occluded shape, or a “below/left-of” configuration that depicted an occluder to the bottom and to the left of the occluded shape (see Figure 3).

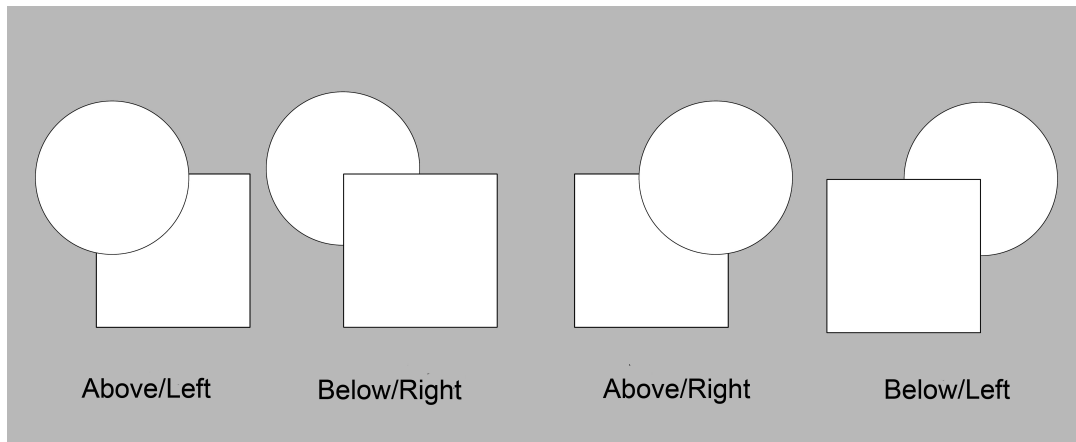


Figure 3: Examples of stimuli that combine a value on the “left-of/right-of” relation with a value on the “above/below” relation.

It is important to note that this experiment worked under the expectation that when someone is presented with a relationally ambiguous exemplar that simultaneously represents a value on two different relations, but where learning one is sufficient for task completion (like deciding whether the exemplar is part of a category), that only one will be learned. The reason for this expectation was that relational reasoning is an explicit process that taxes working memory—the more relations that one entertains, the more working memory is taxed (Doumas et al. 2008). However, working memory is limited, and so people should typically stop working when they have a sufficient answer³.

Priming

As previously noted, primes were designed to potentially capture exogenous visual attention. They were made up of white circles with black outlines that were 150-pixels in size. The circles were presented in either a vertical or horizontal fashion. If the prime was a horizontal prime, then those circles appeared horizontally aligned along the middle of the screen; if the prime was a vertical prime, then those circles appeared vertically aligned along the middle of the screen. In both cases, there were two circles that were spaced 540-pixels away from each other, spread out around the center in the specified direction.

³ While this expectation was generally grounded in the expectation that relational reasoning involves working memory, and working memory is limited, there are other examples of literature that support this expectation. For example, the RULEX model proposed by Nofosky, Palmeri, and McKinley (1994) suggests that people tend to use category descriptions that attend to fewer stimulus dimensions when possible.

Priming would begin with one circle blinking on for 500 ms, then blinking off. There would then be a 100 ms delay, then the other circle would blink on for 500 ms on the opposite half of the screen before also blinking off. Priming proceeded by cycling back and forth between those circles in this way (see Figure 4). The vertical prime was designed such that tracking the circles would require vertical saccades and therefore prime the “above/below” relation, while the horizontal prime would require horizontal saccades and therefore prime the “left-of/right-of” relation. It is important to note that participants were not told to watch the circles. However, participants were left alone with no distractions. Thus, while we cannot confirm that they visually tracked the circles, it was expected that the visuospatial prime might capture their exogenous visual attention.

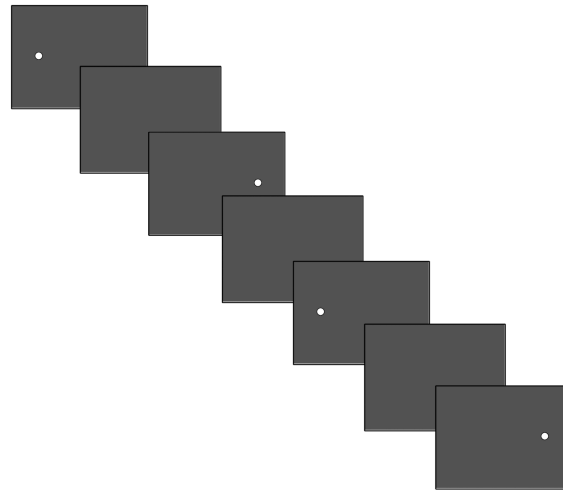


Figure 4: An example of how two priming cycles would progress over time (where time is depicted as movement from left to right). For example, in this case, it would be expected that the attention required to track the balls across their different locations might prime the horizontal rule.

Procedure

Participants were assigned to one of three groups: a control group that received no prime, a vertical prime group, or a horizontal prime group. All participants began by sitting at a computer with a 2560-by-1440 pixel monitor, which ultimately showed stimuli presented in an experiment space of 1440-by-900 pixels.

They were told that they would see pairs of shapes, and that each pair would be positioned according to a “rule”—they were also told that they would not be told the rule (see Appendix A for exact instructions). Given that this was a feedback-learning paradigm, they were instructed to determine the rule by trial-and-error using the feedback provided each time an answer was entered. Participants in the priming conditions were also told that they might occasionally see “blinking dots”, which were just the computer attempting to generate the next set of stimuli.

Participants began with a “training phase” of the task. If participants were in a priming condition, this phase began with five iterations (consisting of one ball in each location) of priming in the condition-appropriate direction. Priming was repeated after every five trials.

During this phase, all participants saw a fixation cross for 1500 ms, then an exemplar. The training phase randomly selected a pair of “training rules” in order to conflate a relative location on the horizontal axis with a relative location on a vertical axis. Thus the training phase would include only “above/left-of” and “below/right-of” pairs, or only “above/right-of” and “below/left-of” pairs. One pair would be randomly associated with the “A” key, and the other to the “L” key, however the keys were described as representing when shapes “followed the positioning rule” or “did not follow the positioning rule”. Participants would then press a key for every exemplar, and “*Correct*” or “*Incorrect*” would follow each press. It is important to note that “Correct” key assignment was randomly assigned for each participant.

Since the values across the two relations were conflated, participants could learn a horizontal rule, a vertical rule, or both rules (where both rules can be defined as any rule in which a value on both dimensions was appreciated). For example, if a participant’s training rules were “above/left-of” and “below/right-of”, where “above/left-of” was assigned to the “A” key, then she could learn that “A” needed to be pressed whenever the occluder was to the left of the occluded shape, or she could learn that “A” needed to be pressed whenever the occluder was above the occluded shape, or she could learn that she needed to press “A” whenever the occluder was above and to the left of the occluded shape. As a result, the visuospatial priming was always consistent with one rule, and inconsistent with another rule.

Training began by presenting 8 exemplars of the same training rule, and then switched to random assortment of exemplars representing the two training rules. For example, the training condition could proceed presenting eight exemplars of “above/left-of” followed by a random sequence of “above/left-of” and “below/right-of”. This training regiment was selected based on Clapper (2009), who claimed that this sort of presentation would increase ease of learning in dichotomous category-learning tasks. The initially presented rule was counterbalanced across participants in each condition.

Once the initial 8 training trials were complete, the experiment began counting each participant’s correct responses. Participants continued to see pairs of shapes (and get feedback) until they learned a rule well enough to correctly classify 10 exemplars in a row.

When participants reached criterion, they were told that they would continue to see pairs of shapes, but that all feedback as to whether they were correct would stop. The test phase of the experiment then began. If a participant was in a priming condition, priming was stopped.

Participants were then presented with a random order of seven exemplars of each possible variable combination (i.e., “above/left-of”, “above/right-of”, “below/right-of”, and “below/left-of” alignments). The goal of the test phase was to allow the experimenters to determine the rule that the participant had learned and was then applying, which could be achieved by looking at their responses to novel alignment combinations: Since training had conflated a value on the “left-of/right-of” relation with a value on the “above/below” relation in two different ways (each marked by a specific key press), the novel stimuli would contain half of each trained pair. Thus, a response to a novel stimulus would indicate which pair the participant thought the novel pair was like, and therefore whether she learned the “above/below” or “left-of/right-of” rule.

For example, suppose a participant was trained on “above/left-of” and “below/right-of”, where “above/left-of” was associated with an “A” key press, and “below/right-of” was associated with an “L” key press. “above/right-of” and “below/left-of” pairs could be used to determine which rule the participant had learned: If presented with an “above/right-of” pairing, then an “A” key press would indicate that the participant was classifying the stimulus like an “above/left-of” pair. If “above/left-of” and “above/right-of” pairs were classified in the same way, then the participant must have attended to the “above/below” relation (since “Above” is the common relational value between them). Conversely, an “L” key press would indicate that the participant had classified by the “left-of/right-of” rule (see Figure 5).

Once testing was complete, participants were debriefed. The experimenter asked them i) what rule they learned, and ii) if they were in a priming condition, what they thought the experiment was about.

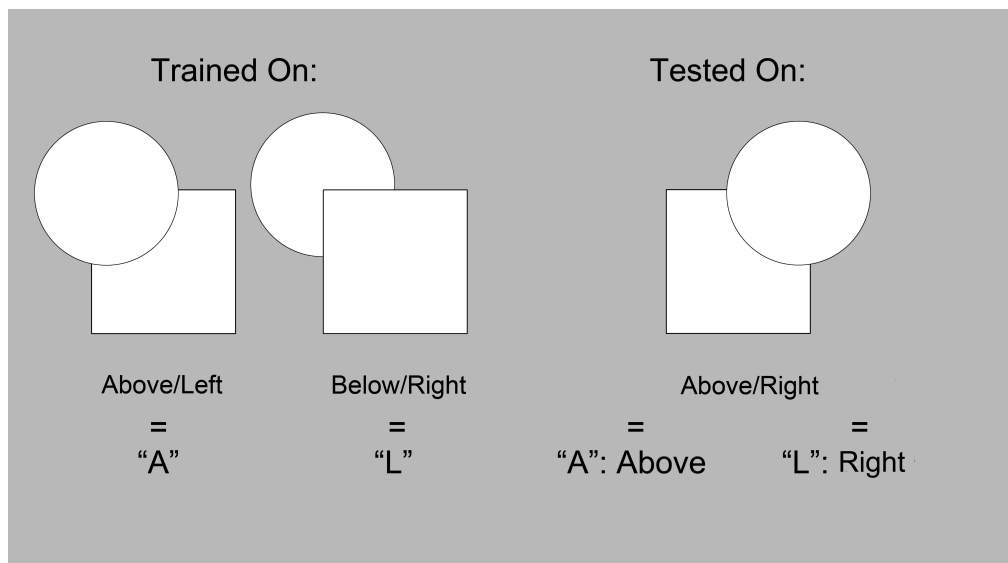


Figure 5: An example of possible training set and test phase exemplars. Imagine the participant was trained on “above/left-of” and “below/right-of” exemplars, where an “A” key press was paired with “above/left-of”, and an “L” key press was paired with “below/right-of”. If that participant were then shown an “above/right-of” exemplar during the test phase, then an “A” key press would indicate that “above/right-of” was being classified in the same way as an “above/left-of” exemplar, while “L” would indicate that it was being classified in the same way as a “below/right-of” exemplar.

Results

No participant made an explicit connection between the visuospatial priming and the category-learning task. With regard to rule learning, participants were considered to have learned a rule if they made no more than 3 inconsistent responses across the 14 novel stimuli during the test trials. For example, if they classified 11 of the novel exemplars by the “left-of/right-of” rule, then they were considered to be horizontal-rule-learners; however if they classified 10 by the “left-of/right-of” rule, and 4 by the “above/below”

rule, then they were classified as no-rule-learners. The only exception was in the case of dual-rule learners (i.e., those who were considered to have learned both rules): because the task instructions associated one key with exemplars that “followed the rule” and the other key with exemplars that “did not follow the rule”, dual-learners could produce data that looked identical to participants who learned nothing. As a result, we relied upon the debriefing answers such that participants were considered to have learned both rules if they i) reported having learned both rules, and ii) made no more than three classifications inconsistent with the combined rule reported (i.e., where a novel exemplar was classified a “did not follow the rule” exemplar). Participants who did not learn any rule up to criterion were eliminated from subsequent analysis.

An overall chi-squared test showed a significant difference between conditions ($\chi(4)=10.433, p<.05$) (see Table 1), suggesting that the priming did have an effect. Interestingly, the control condition showed a strong bias towards a horizontal rule, and so post-hoc testing showed a significant difference between the control condition and the vertical priming condition ($\chi(2)=8.1591, p<.05$), and a difference approaching significance between the vertical and horizontal priming conditions ($\chi(2)=5.9297, p=.05$), but no difference between the horizontal and control conditions ($\chi(2)=0.8509, p=.65$).

Table 1: The number of participants who learned each rule, organized by priming type.

	Control	Vertical Prime	Horizontal Prime
Horizontal Rule Learned	13	7	15
Vertical Rule Learned	7	17	9
Both Rules Learned	11	5	8
No Rules Learned	4	6	4

Discussion

The results from this experiment showed that participants were more likely to learn whatever category rule they were primed to learn. Thus, they suggest that visuospatial priming can affect which relational category is learned when multiple are equally possible. They further suggest that relational reasoning can, in general, be primed by the axis along which the movement of visual attention is attracted.

Interestingly, the data also showed other trends worth discussing. For example a number of rule-learners did not learn the “left-of/right-of” rule, nor the “above/below” rule, but instead learned some combination of the two (thus, we called them “dual rule learners”). One possible explanation (that is potentially contradictory to our original

hypothesis) is that they explicitly learned both rules (e.g., they might have learned “up” and “left-of”). Alternatively, they might have learned some rule that conflates the two spatial locations into a single relation (e.g. some version of “up-left”). At this time, it is unclear as to which of these possibilities is the case. It is also unclear as to why such learners were especially prominent in the control condition (see Table 1). Future research may need to determine which possibility is more likely and why. That said, the answer to this question is not central to our current research question—what is crucial is that such learners did not prioritize the primed relation over other possibilities.

Furthermore, we observed a bias towards horizontal rule learning in the control condition (see Table 1). While this result was also unexpected, there are two possible explanations for why it might have occurred. First, it seems possible that the horizontal alignment of the answer keys could have had a priming effect of its own (“A” is left of “L” on keyboard used run this experiment). While this possibility requires further research of its own, it would speak to the power of relational priming if it were the case. Second, existing literature highlights the importance of the horizontal axis in actor/patient designations. For example, Chatterjee et al. (1995, 1999, 2001) found that people have a tendency to describe relational scenes with the actor to the left of the patient. A horizontal rule would allow reasoners to follow this tendency, while the vertical rule would explicitly violate it. Notably, this result is congruent with the idea that visuospatial factors are important for relational processing, and suggests that (primed or not) they shape what relation is recognized and subsequently learned.

That said, the generalizability of these findings are limited: as previously noted, relations like *left-of* and *above* are reasonably simple relations that have an easily imaginable relationship with horizontality and verticality (respectively). However, some other relations seem more complex and less obviously related to spatial alignments. For instance, *chases* not only involves a relative location between an actor and a patient, but also movement, and the actor’s intention behind that movement (i.e., that it is trying to catch the patient). As a result, it is necessary to explore whether such priming can also affect the processing of less obviously-spatial relations. Chapter 4 investigates this issue.

Chapter 4

Can Vision and Space Shape More Abstract Relations?

The methodology from Chapter 3 was ideal for determining whether relations can be primed when those relations possess obviously different spatial schemas and an equal degree of abstractness. However, one stated goal of this project is to test whether visuospatial priming can affect a range of relations, varying in their level of abstractness. As a result, a different methodology must be used.

To this end, this chapter is based on the fact that relational reasoning sometimes requires one to not only overlook object attributes, but also similarities between those attributes. For instance, if one is shown two cups sitting beside each other and asked how they are related, one will need to actively ignore their identical features (i.e., the fact that both objects were cups) in order to identify a “beside” relation. However, (as described in previous chapters) ignoring object attribute similarities can be difficult.

Here, time pressure was exploited for the purpose of studying how and to what degree visuospatial priming can affect whether similarities across object attributes can be overlooked in favor of relational ones. The method was inspired by response-deadline studies on similarity judgments, which have suggested that people will make judgments in favor of object attributes at short time scales (somewhere between 700 and 1000 ms), but more relational judgments at longer time scales (Goldstone & Medin, 1994; Gentner & Markman, 1997). Thus, we had participants complete analogy tasks but varied the amount of time that the base analog was presented, and asked whether the amount of time required to make a relational mapping over a mapping based on object attributes (when both were present) could be manipulated with the sort of priming used in Chapter 2⁴.

In order to both prime a variety of relations over the course of the experiment, and to disguise the presence of the priming, participants were told that they were taking part in a study about multitasking in which they would be constantly switching between two unique tasks—a “ball counting” task and a “find the thing doing the same thing” task. Participants consistently completed one counting trial, which was actually the priming task, followed by one “find the thing doing the same thing” trial, which was actually the analogy task. The goal was to prime each relation with a visuospatial stimulus just before completing an analogy task involving that relation.

While the priming was similar to that found in Chapter 3, the analogy task was unique and employed pictorial crossmapping analogy problems that were adapted from Richland, Morrison, and Holyoak (2006). Crossmappings are problems in which the objects in the base analog (the relation being mapped from) play different roles in the target analog (the relation being mapped to). For example, the relational statement “the dog chases the cat” specifies two elements (a dog and a cat) involved in a chasing relationship; the statement “the cat chases the dog” specifies the same objects, however those objects are playing opposite roles. As a result, one must ignore similarities

⁴ Note that because time’s effects on relational reasoning are not entirely clear in the existing literature, an additional experiment was run. Please see Appendix B for data suggesting that crossmapping performance moves towards feature-based mappings as base-analog presentation time decreases.

involving object attributes in favor of roles in order to reason relationally. Our paradigm displayed problems of this nature, but limited the temporal exposure of the base analog.

The relations used were selected because they were expected to have underlying vertical or horizontal image schemas (as described in Richardson, Spivey, Edelman, & Naples, 2001; Richardson et al., 2003; Chatterjee, 2010; Meteyard, & Vigliocco, 2009). We reasoned that if spatial image schemas are part of a relation's representation (i.e., that they are part of a relation's features), or if attention can be directed in a way that is congruent with a presented relation, then it should be possible to exploit ocular-movements for the purposes of priming. Thus, like in Experiment 1, priming involved a vertical or horizontal visuospatial stimulus, and it was expected that these primes would access those image schemas or direct attention in order to promote more accurate relational mappings (over object attribute mappings) in congruent priming conditions across time scales.

Participants

Participants were 243 undergraduate students from the University of California, Merced. They were recruited through the school's participant pool and received course credit for participation. All participants were over 18 years of age and had normal to corrected-to-normal vision. Data from 18 of those participants were not included in analysis due to an inability to sufficiently complete the task (i.e., they could not learn the task procedure and were unable to progress through trials in the required order).

Analogy Stimuli

As previously noted, the stimuli consisted of pictorial scenes adapted from Richland et al., (2006). Each contained six objects dispersed around a black and white drawn image; all images were 720-by-450 pixels in size and included both living and non-living things. The images were presented on a black background. All stimuli were normed by having two experimenters a) count the number of objects in each scene, and b) state the relation that was shown. Full agreement was found.

The experiment used 64 of these scenes depicting 32 different relations. Eight relations were used for training trials, 8 were used as filler items (shown in between target trials), 8 were relations thought to possess horizontal image schemas, and another 8 more were relations expected to possess vertical image schemas (see Table 2). Five of 32 verbs were taken from Richardson et al., (2003), where they had already been normed to show greater than 70% agreement in their image schematic orientations. To expand the set of verbs for this experiment, 27 additional verbs were included. These additional verbs were normed via a simple Mechanical Turk survey that asked 15 participants to classify the verbs as "horizontal", "vertical", or "neutral". Mechanical Turk is an online work platform provided by Amazon where participants can be paid small amounts (15 cents in this case) to complete short tasks. The key items used received greater than 70% agreement on their image schematic orientations.

Table 2: The list of relations used in Chapter 4’s experiment, organized by type (those with vertical image schemas, those with horizontal image schemas, those with neutral image schemas, and those used for training).

Vertical	Horizontal	Fillers	Training
Pouring-on	Chasing	Kissing	Riding
Dropping	Pulling	Playing-with	Talking
Hanging-from	Pushing	Resting-on	Balancing
Carrying	Kicking	Cooking	Feeding
Lifting	Towing	Cleaning	Sheltering
Reaching-for	Points-at	Driving	Scolding
Bombing	Hunting	Opening	Hitting
Climbing	Gives-to	Performing-for	Brushing

Each relation was instantiated in two different images, creating a base analog (i.e., an image that was to be mapped from) and a target analog (i.e., an image that was to be mapped to). All analogy problems were created such that each relation was depicted in a way congruent with its image schema (e.g., *chasing* was depicted horizontally). In all cases, the base analog was shown in the top half of the screen, while the target analog was shown in the bottom half of the screen. The base analog had one item circled in red, while the target had the numbers 1 through 4 beside different objects, each representing possible answers. Numbers were assigned haphazardly to items in the images. In key trials, the enumerated items included a relational match to the circled item, an object attribute match to the circled item, and two distracter items (though note that in filler trials, the enumerated items included a relational match and three distracter items) (see Figure 6 for examples).

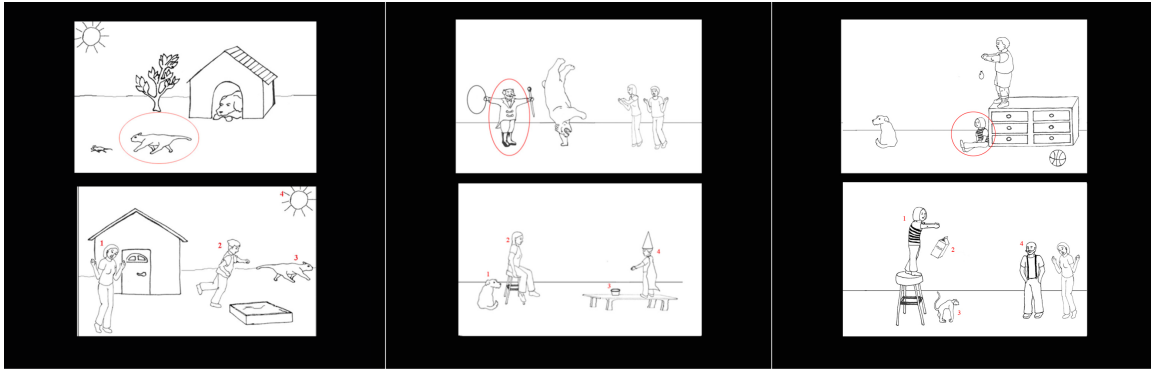


Figure 6: Three stimulus examples from the experiment described in Chapter 4. Figure 6a shows the horizontal verb *chasing* depicted such that *chasing*(cat, mouse) must be mapped to *chasing*(boy, cat). The answer of “boy” would make the relational mapping, while the answer of “cat” would make the featural mapping. Figure 6b shows the filler item *performing-for*, where *performing-for*(ring-master, audience) must be mapped to *performing-for*(boy, audience). Here, the audience looks different across images and no exact featural matches are present. Figure 6c shows the vertical verb *bombing*, depicted such that *bombing*(boy, girl) must be mapped to *bombing*(girl, monkey). Here, the answer “monkey” would make a relational mapping, while the answer “girl” would make the featural mapping.

Priming

Like in Chapter 3, the primes were made up of 150 pixel-large circles with a thin black outline. Each round of priming involved a total of ten circles, a random number of which were colored red, while the rest were white.

The circles blinked on and off one at a time at specified locations on the screen. Again, like in Chapter 3, the circles were positioned across the screen from each other, such that if one looked from one circle to the next, it required a linear eye movement of a specific linearity. In key trials, the locations of the circles required movements that were congruent or incongruent with the expected image schema of the depicted relation (horizontal or vertical). Filler trials, however, were randomly paired with a priming alignment since they were included only to ensure that participants did not make an explicit connection between the moving dots and the stimuli. Thus, these filler trials were randomly assigned a priming alignment at the beginning of every trial for every participant. They could be vertical, horizontal, or even diagonal.

Procedure

To start, participants were told that the experiment was about multitasking, and that two different tasks would be interleaved trial-for-trial. They were also told that they would always complete one “ball counting” problem, during which they would count the number of red balls shown in a given sequence, then they would switch to a “find the thing doing the same thing” problem where they would identify the item in the target analog that they thought was “doing the same thing” as the item circled in the base analog.

It is important to note that while telling participants to “find the thing doing the same thing” may seem heavy handed, analogy research generally suggests that relational

cognition is difficult, and people often do not engage in it unless explicitly directed to do so (e.g., see Gick & Holyoak, 1980, 1983; Spellman, et al., 2001). The goal of the instructions was to give participants a clear understanding of what a “correct answer” might look like. That said, we admit that these instructions may limit the degree to which this study can comment on free relational recognition.

The priming task was presented on a 1920-by-1080-pixel sized monitor positioned on the right hand side of the desk, while the analogy task was presented on a 2560-by-1440-pixel monitor on the left. The tasks were presented on different, and differently-sized, screens in order to avoid priming a specific location on the screen where the analogy problems would be shown.

The experiment design was a 2x5 between-subjects factorial design. Participants were randomly assigned to either a congruent or incongruent priming condition and to one of the five analog presentation times. So, for example, if a participant was assigned to the congruent 500 ms condition, and she was completing the “*chasing*” trial (where “*chasing*” is expected to have a horizontal image schema), then she would complete a ball counting task where the circles blinked on and off in a horizontal way, followed by the “*chasing*” analogy problem where the base analog would be displayed for 500 ms. If the next trial involved the “*lifting*” problem (where “*lifting*” is expected to have a vertical image schema), she would then complete a ball counting task where the circles blinked in a vertical way, then complete the “*lifting*” analogy problem where the base analog would again only be shown for 500 ms.

After participants were assigned to a condition, all participants had both tasks explained to them, and then the experimenter guided them through the 8 training trials. The experimenter provided verbal cues to switch tasks during this phase to ensure that the participants stayed in sequence. Cues included “switch computers”, or just “switch” after the initial training trial. The experimenter stopped providing cues altogether when the participant was able to switch tasks on his or her own.

When training was complete, participants began the active trials, which were self-paced. The relations with horizontal image schemas, the relations with vertical image schemas, and the filler relations were randomly ordered for each participant. Performance on key trials was measured in two ways: first the number of problems that were successfully solved with the relational mapping, and then by the number of problems incorrectly answered with the distracter object attribute match over the relational match and other distractors.

Results

A two-way ANOVA showed that priming congruency had an effect on overall accuracy (i.e., the number of relational mappings made) on key trials such that those in the congruent priming conditions did better than those in the incongruent priming conditions ($F(1,224)=47.890, p<.01$). In other words, they were more likely to select the correct answer than one of the three distracter items. It also showed that the presentation time of the base analog had an effect such that those in the longer temporal intervals also did better than those at shorter temporal intervals ($F(4,224)=3.976, p<.01$).

There was no interaction between the condition and the presentation times ($F(4,224)=.069, p=.991$), however, planned comparisons by condition showed significant

differences at all presentation times (see Figure 7 and Table 3). This result suggests that participants in the congruent conditions tended to produce a lower number of inaccurate crossmappings on key trials, not only globally, but also at each time step.

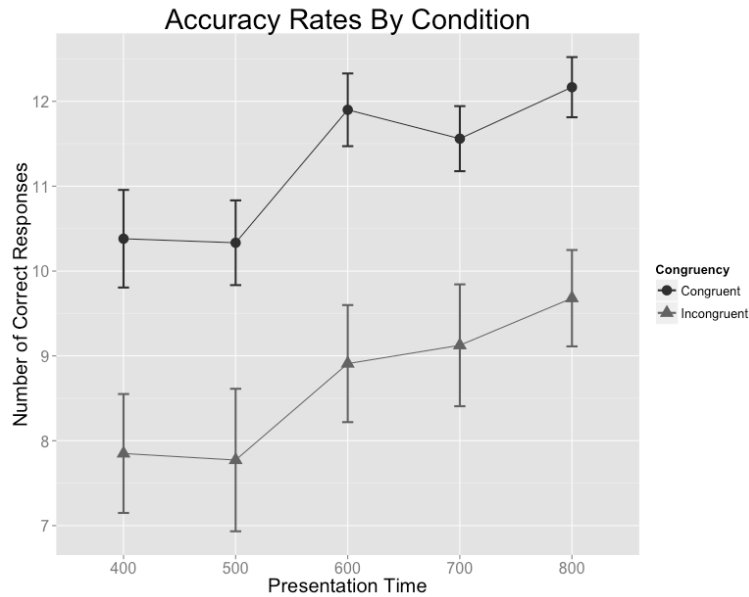


Figure 7: A graphical representation of the number of relational mappings made in the experiment presented in Chapter 4, organized by congruency condition. The x-axis represents the possible amounts of time that the base analog could be displayed, while the y-axis represents the raw number of questions answered (16 were possible). Error bars represent the Standard Errors.

Table 3: Overall accuracy on key trails in the experiment presented in Chapter 4, organized by condition. The final column shows the results from planned comparisons (protected t-tests with an alpha level of .01). Stars show comparisons where variances were unequal between groups, and the degrees of freedom were adjusted to correct for it.

	Congruent	Incongruent	Planned Comparison
400	$M=10.38$ $SD=2.64$	$M=7.85$ $SD=3.133$	$t(39)=2.804, p<.01$
500	$M=10.41$ $SD=2.26$	$M=7.77$ $SD=3.94$	$t(33.479)=2.723, p<.01^*$
600	$M=11.90$ $SD=1.92$	$M=8.91$ $SD=3.24$	$t(40)=3.598, p<.01$
700	$M=11.56$ $SD=1.92$	$M=9.13$ $SD=3.52$	$t(35.234)=2.991, p<.01^*$
800	$M=12.17$ $SD=1.74$	$M=9.68$ $SD=2.84$	$t(40.007)=3.715, p<.01^*$

Another ANOVA showed that priming congruency had an overall effect on the number of featural matches selected ($F(1,224)=49.554, p<.01$). This result means that those in the congruent conditions were less likely to specifically select the featural distracter item in key trials than those in the incongruent conditions. Likewise, it was also found that the presentation time of the base analog had an effect on this measure ($F(4,224)=3.376, p<.05$), suggesting that those at longer time steps were also less likely to select the featural distracter item on key trials.

Once again, while there was no interaction between congruency and presentation time ($F(4,224)=.180, p=.949$) planned comparisons showed significant differences between the congruency conditions at the 500, 600, 700, and 800 ms time steps. It was approaching significance at the 400ms time step, with an alpha level of .01 (see Figure 8, and Table 4). Thus, participants in the congruent priming conditions tended to produce a lower number of featural mappings on key trials, both overall and at each time step.

Finally, one last two-way ANOVA was run in order to test the generalizability of our stimuli post-hoc. Specifically, we ran an item analysis common within psycholinguistics, originally outlined by Clark (1973). This analysis involves running a two-way ANOVA where stimuli were treated as the random factor (instead of the participants) in order to ensure that the experimental results were not an artifact of the specific items used (rather than a phenomenon that can be generalized across stimuli). It showed similar trends to the reported participant statistics with regard to overall problem accuracy: The temporal presentation of the base was a significant factor ($F(4)=3.531, p<.01$), along with the priming condition ($F(1)=13.768, p<.01$). Again, there was no interaction ($F(4)=.146, p=.964$).

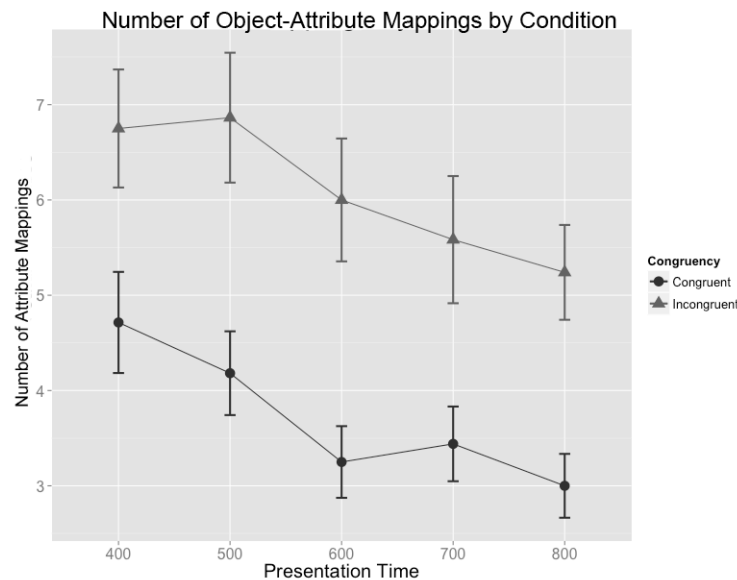


Figure 8: A graphical representation of number of featural mappings made in the experiment presented in Chapter 4, organized by congruency condition. The x-axis represents the possible amounts of time that the base analog could be displayed, while the y-axis represents the raw number of questions answered. Error bars represent the Standard Errors.

Table 4: Number of featural mappings made over relational mappings on key trials in the experiment presented in Chapter 4, organized by condition. The final column shows the results from planned comparisons (protected t-tests with an alpha level of .01). Stars show comparisons where variances were unequal between groups, and the degrees of freedom were adjusted to correct for it.

	Congruent	Incongruent	Planned Comparison
400	$M=4.71$ $SD=2.43$	$M=6.75$ $SD=2.77$	$t(39)=2.504, p=.017$
500	$M=4.18$ $SD=2.06$	$M=6.86$ $SD=3.20$	$t(35.07)=3.307, p<.01^*$
600	$M=3.25$ $SD=1.68$	$M=6.00$ $SD=3.02$	$t(40)=3.591, p<.01$
700	$M=3.44$ $SD=1.96$	$M=5.58$ $SD=3.52$	$t(37.344)=2.769, p<.01^*$
800	$M=3.00$ $SD=1.64$	$M=5.23$ $SD=2.49$	$t(47)=3.703, p<.01$

Discussion

The findings of this experiment demonstrate three things: First, they suggest that priming congruency affects the probability of selecting a featural mapping over a relational mapping on a crossmapping analogy problem overall. Second, they suggest that longer presentations times of the base analog also affect the probability of selecting that featural mapping overall. And third (and perhaps most importantly), they suggest that priming will significantly affect the number of featural mappings made, not only at longer presentation times, but at shorter ones as well. In other words, visuospatial priming can alter the likelihood that one makes a featural match when one is under time pressure.

When considered with the results found in Chapter 3, it seems possible to claim that this visuospatial priming works on a variety of relations with varying levels of explicit spatiality and abstractness (so, not just on spatial relations such as “above”, but also on relational verbs such as “chases”). However, it is important to note that while this experiment demonstrates that priming a spatial orientation congruent with a relation’s representation can affect reasoning about that relation, it cannot not comment on the mechanisms by which that priming works. In all cases, relations were depicted congruently with their image schemas, and so congruently priming one involved congruently priming the other. This is particularly problematic because, as it was pointed out in Chapter 2, there are at least two possible explanations: content-based priming that accesses a relation’s underlying features, and ii) attention-based priming that changes

how one interacts with a scene such that one is more likely to notice a given relation. Thus, the next chapter will begin to pull these apart.

Chapter 5: What's Responsible?

Teasing apart representational priming from attentional priming is difficult because the two typically co-occur, especially in visually depicted relational exemplars. For example, it seems difficult to imagine how one might depict a *lifting* relationship only on a horizontal axis; in fact, at some point a horizontal *lifting* relationship could start to look quite a bit like *pushing*. As a result, priming the spatial features of a vertical relation like *lifting* through, say, eye movements could also prime one's attention to vertical alignments and ultimately conflate the two types of priming.

There are, however, select verbs that can be represented spatially-atypically. For example, *chasing* has been associated with a horizontal axis (see Chapter 4), but vertical instantiations of it are possible and reasonable. For example, a cat can chase a mouse up a tree (see). Such relations provide a unique opportunity to prime visual attention and representation content separately. So, it might be possible to congruently prime chasing's image schema using horizontal eye movements, while incongruently priming the visual scan patterns needed to view the scene. The experiment presented in this chapter did just this.

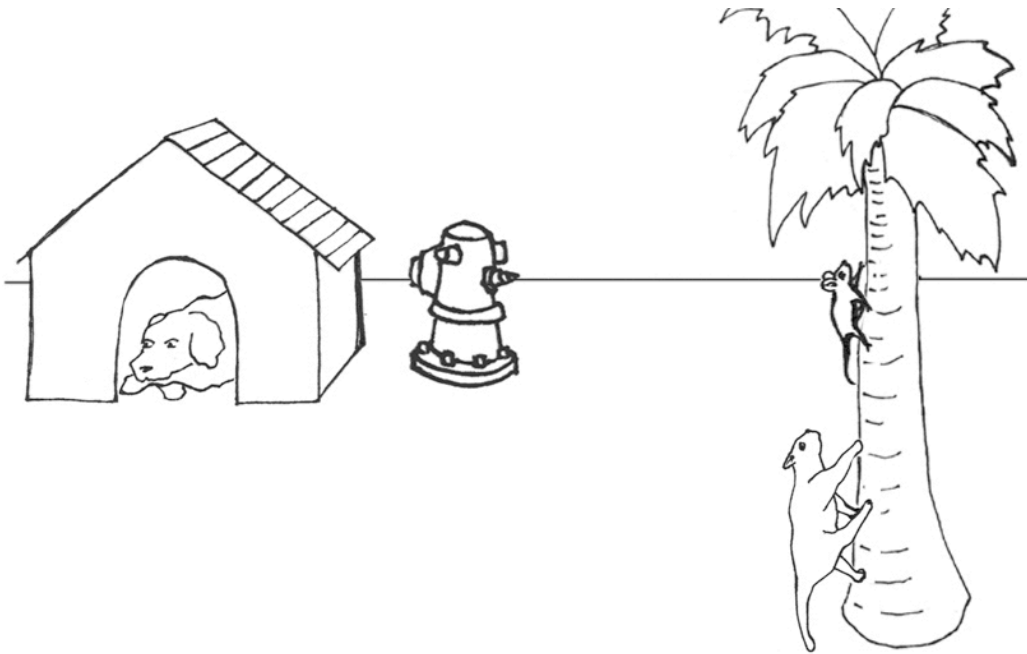


Figure 9: A stimulus example from the experiment in Chapter 5, showing a vertical chasing relationship. Here, *chasing*(cat, mouse) is depicted.

In what follows, “directionally flexible” verbs were used in an experiment highly similar to the one found in the previous chapter. Thus, participants cycled between a

priming task and an analogy-making task and the number of relational mappings was tracked. However, in the current study, the analogy stimuli depicted relations opposite to their known-image schemas. The experiment's conditions were defined by whether the priming was congruent with the visual attentional pattern necessary for noticing the relation in the given scene or with the relation's representational image schema.

Given how little is known about relational priming, it was impossible to know which type of priming would be more effective. As a result, the research hypothesis was simply that the two conditions would produce different results (i.e., analyses was two-tailed).

Participants

Participants were 70 undergraduate students from the University of California, Merced. Again, they were recruited through the school's online participant pool and received course credit for participation. All participants were over 18 years of age and had normal to corrected-to-normal vision. Data from 6 of those participants were not included in analysis due to an inability to sufficiently complete the task (again, these participants could not learn the task procedure and were unable to progress through trials in the required order)

Analogy Stimuli

Stimuli were almost identical to those found in Chapter 4, however, the relations used, and so the exact images, differed. Here, relations had dominant spatial image schemas, but were capable of being expressed along the opposite axis (see Table 5). For example, as previously discussed, while "chasing" is known to have a horizontal image schema, it is possible for chasing to take place in a vertical direction.

Mechanical Turk was again used to norm the verbs and confirm/identify verbs with 70% or greater agreement across respondents ($N=14$). Norming involved a simple survey format, where participants read a relation and then selected whether they thought of it as a "vertical", "horizontal", or "neutral" verb. Ultimately, five verbs with vertical image schemas were selected then depicted horizontally, another five with horizontal image schemas were selected then depicted vertically, and six verbs with no significant image schemas were used as fillers. Six more non-directional verbs were used for training.

Priming

Priming was identical to that found in Chapter 4.

Table 5: The list of relations used in the current experiment, organized by type (those with vertical image schemas, those with horizontal image schemas, filler items, and those used for training).

Vertical	Horizontal	Fillers	Training
Burying	Chasing	Kissing	Riding
Climbing	Giving	Playing-with	Talking
Drilling	Hunting	Sheltering	Feeding
Launching	Pointing	Brushing	Driving
Reaching	Pulling	Opening	Cooking
		Performing-for	Scolding

Once again, the selected verbs were depicted using drawn images analogous to those found in Richland et al. (2006) and, once again, they were normed to represent the specified relation, and to have six items in each image (norming proceeded in the same way as in Chapter 4).

Procedure

There were only two differences between the current method and that found in Chapter 4. First, only a single time-step was used since the effects of time were already known from that previous experiment. Thus, the base analogy was only shown for 400ms for the entire collection of analogy problems across all participants. This particular amount of time was chosen because it was the lowest interval used in the previous experiment. Second, while conditions were still defined based on the nature of the priming, the priming was either “*content congruent*” or “*attentionally congruent*”. In no case were both congruently primed. So, consider the earlier *chasing* example: in this case priming was vertical, matching the visual scan patterns necessary for noticing chasing in that given scene, or horizontal, matching the image schema of chasing.

Results

Overall accuracy rates (i.e., number of relational mappings made) were collected and then compared across priming conditions. An independent-samples t-test was used for this comparison because only a single time step was used and because each participant only saw a single priming condition. While a Levene Test for Equality of Variances showed a significant difference in between-group variances ($F=4.726, p<.05$), a correction was made and still showed a between-groups difference ($t(61.60)=2.23, p<.05$) byway of a independent samples t-test. Specifically, those in the attention-based congruent priming condition ($M=5.11, SD=1.57$) performing better than the incongruent priming ($M=4.06, SD=2.20$) (see Figure 10).

Like in the previous experiment, the number of attribute mappings (i.e., the number of mappings where the feature mapping was made) were also calculated by condition. Again, while a Levene Test for Equality of Variances showed unequal between-group variances ($F=8.538, p<.05$), another correction was made and again an independent-samples t-test showed a significant difference by priming group ($t(59.501)=2.828, p<.01$). Again, those in the congruent priming condition ($M=4.36, SD=1.45$) made fewer attribute mappings than those in the incongruent condition ($M=5.69, SD=2.32$) (see Figure 11).

Once again, an item analysis was run, which used the images as the random factor. Given that the two experimental groups had a different number of participants, the proportion of correct responses to incorrect responses was calculated by image. A repeated-measures t-test was then calculated, and showed a significant difference between images ($t(9) = 3.073, p < .05$) based on priming condition ($M = 52.59, SD = 38.24$ for the congruently primed stimuli, and $M = 40.00, SD = 29.08$ for the incongruently primed stimuli). This result suggests that the results found can be generalized beyond the stimuli used in this case (again, see Clark, 1973).

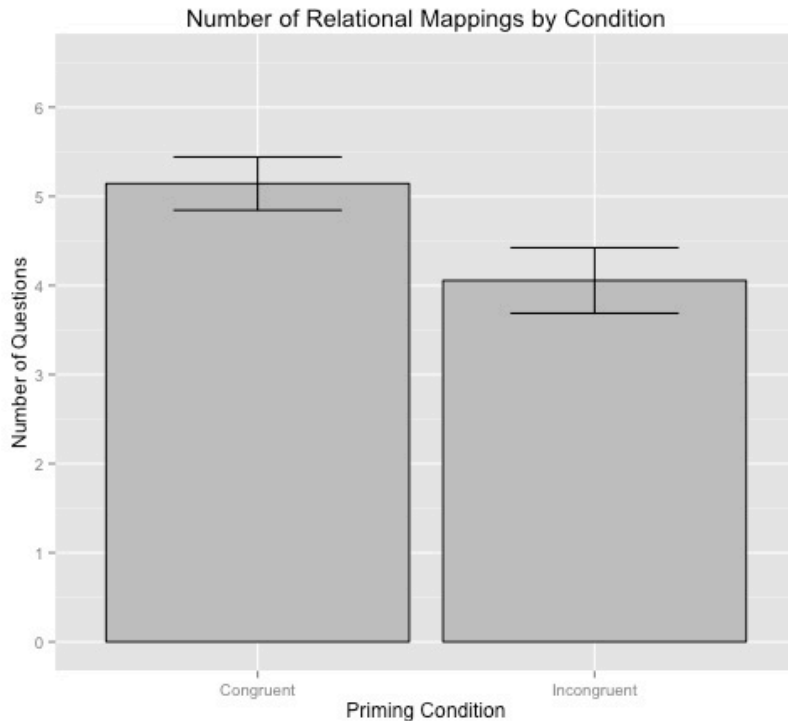


Figure 10: A graphical representation of the number of relational mappings made in the experiment presented in the current study. The x-axis represents the priming conditions, while the y-axis represents the raw number of questions answered (where 10 were possible). Error bars represent the Standard Errors.

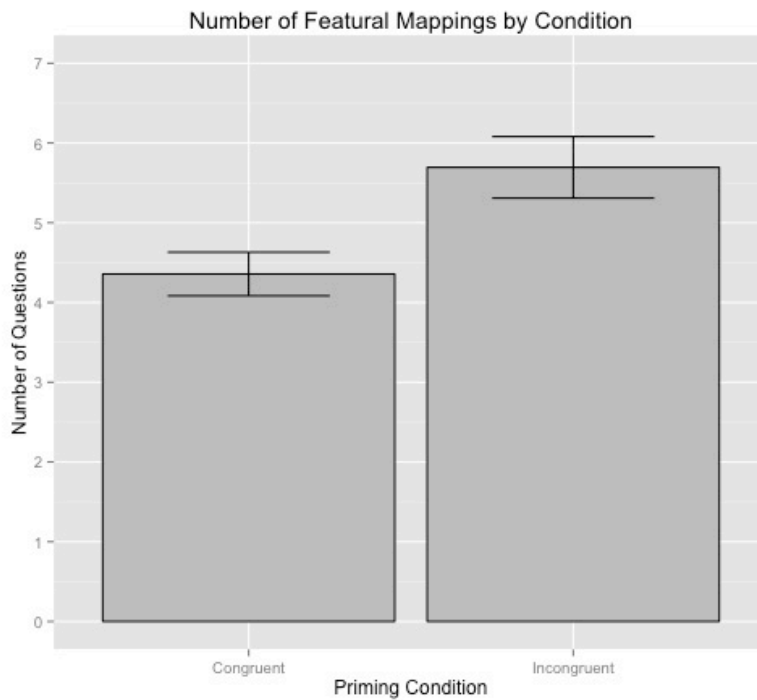


Figure 11: A graphical representation of the number of featural mappings made in the experiment presented in the current study. The x-axis represents the priming conditions, while the y-axis represents the raw number of questions answered (where 10 were possible). Error bars represent the Standard Errors.

Discussion

This experiment is the first in this series to gain insight into the mechanisms of priming, and not just on the overall possibility of it occurring. The results showed that attentional priming congruent with the type of visual strategy necessary to view a given relation may affect a participant's probability of making an analogical mapping using that relation. As a result, it seems that attentional priming can not only change the trajectory of relational reasoning, but also make it more likely to occur.

Importantly, this priming effect was produced over priming that targeted the representational content of the relations used (i.e., of their image schemas). There are a number of candidate explanations for this result. First, it could be the case that representing a relation contrary to its expected image schema simply makes it less prototypical, and so more difficult to recognize. For example, *pulling* something vertically is reasonably unusual, and could look very much like *lifting*; longer gaze times (or even slightly different display angles) might be required to recognize it over the vertically-oriented alternative relations depicted in a scene. Thus, in this case, it might be that the atypically represented relations simply did not get recognized in the short base analog presentation times and so the representational priming could not take effect.

Alternatively, it could also be the case that representational priming of relations is simply not possible. If this is the case, then the priming effects seen in this experiment (and the previous ones) may be due to a prime's ability to direct participants' attention along the axis that holds relationally relevant items. For example, moving one's eyes horizontally might create an attentional bias to look horizontally at some subsequent

stimuli; if that stimuli possesses a relation that is depicted along that axis, then it might increase the probability of noticing it, recognizing it, and ultimately reasoning about it.

Unfortunately this experiment is not sufficient for selecting one of these candidate explanations over the other. To the point, this experiment simply shows that attentional priming can overpower representational priming in visual scene analogy problems—it does not show that representational priming is not possible in a global sense. While it is reasonable to expect that these results will generalize to other relational tasks, further research should attempt to determine whether they extend to tasks presented in non-visual modalities. Such experiments might be able study representational priming without worrying about the degree to which the stimuli are prototypical of the relations used.

These results also prompt further questions about the role of attention in relational priming. It is important to notice that attention and movement were inherently conflated in the current methodology: participants moved their eyes in order to attend to the prime. As a result, it seems possible that the movement itself might have been responsible for at least part of the priming effect. Thus, it seems necessary to ask whether attention *without* directed movement might be sufficient for priming a relation.

Chapter 6: Isolating Attention

To date, little is known about the interaction between attention and relational cognition and, like the findings presented in Chapter 5, what is known has been inherently tied to movement. For example, Franconeri et al. (2012) looked at the role of vision in the processing of spatial relations (such as “to the left of” or “to the right of”) and argued that the visual system will register such relations, not holistically, but by processing each relationally-relevant object sequentially. This “shift” account predicts that attention and saccades between objects help to encode spatial relations, and that at least one shift is necessary for recognizing them. For example, if one is looking at a scene with a series of shapes, then one might recognize that “one shape is to the left of another” by looking at the left one then making a saccade to one on the right. Franconeri et al. (2012) used eye-tracking to confirm that such movements occurred prior to making relational judgments.

Franconeri et al.’s (2012) work is noticeably congruent with DORA’s (and its predecessor LISA’s) unique prediction that time (i.e., firing sequence) and role-bindings will be important for recognizing and representing a relation⁵. However, like the methods used in the previous chapters, Franconeri et al.’s findings rely on movement, making it difficult to know whether attention was specifically responsible, or whether movement was a key component.

The current chapter will combine Franconeri et al.’s (2012) use of visual attention with DORA’s prediction that the order in which objects are attended can affect a relation’s representation in order to determine whether visual attention can specifically change what relation is recognized. It will do this in two steps: given that little is known about the relationship between attention and relational reasoning, it will begin by presenting an experiment that determines whether the order in which items are attended can predict which item is bound to the actor role and which is bound to the patient role in pictorial binary relations. It will then present a second experiment that determines whether manipulating visual attention—specifically the object attended to first—can make it more likely that the object is bound to the actor role, and therefore which relation is recognized.

Both experiments will use as paradigm similar to that found in Gleitman et al. (2007), which used eye-tracking to show that gaze can shape the structure of a sentence used to describe a given scene. This study showed participants images and tried to manipulate which item was designated as the actor and which was the patient (e.g., they showed an image of a dog chasing a man and asked whether it could be described by statements like, “The man chases the dog” or “The dog flees from the man”). It found that the item that was looked at first had a significant effect on the structure selected. However, this study only looked at sentence structure (i.e., the actor/patient designations in a given verb); it did not look at whether this designation could change *what* verb or

⁵ Remember that according to DORA one must encode roles and bindings asynchronously across time and so the system does not represent whole relations (e.g., there is no *chases*, only *chaser* and *chased*).

relation was represented/identified entirely. The current studies will specifically test whether the first object that one fixates on in a scene can predict not only which object is treated as the actor or patient, but also what *relation* is explicitly recognized and identified.

This goal will be achieved by using scenes that depict numerous relations at once (much like the real world). For example, a picture of a mother feeding a child might depict a feeding relationship, as well as an eating relationship between the child and the food, a sitting relationship between the mother and a chair, and any number of spatial relationships (next to, beside, etc.; see Figure 12). At some level, relational recognition involves prioritizing one relation over the others, and research question asked here was whether initial visual fixation within a scene is one such factor. First fixations were specifically chosen because they are a measure of visual attention that does not inherently involve movement.

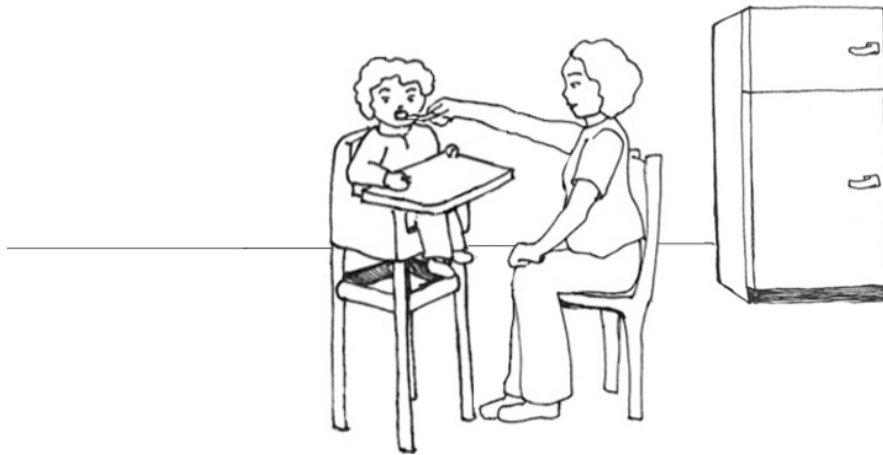


Figure 12: An example of a scene that might be described as “feeding”, but which also depicts an “eating” relationship, as well as numerous spatial ones.

Experiment A

As noted above, this study is a correlational one. It determines whether the first item of fixation can predict which relation is recognized when participants were given an opportunity to answer freely. They were shown multiple relational scenes, and asked to type in whatever relationship they thought was most prominent. Their ocular fixations were tracked throughout the task, and then compared to the relational descriptions provided.

Participants

Participants were 58 University of California Merced undergraduates. They were recruited through the school’s online participant pool and received course credit for

participation. All were over 18 years of age, had normal vision to corrected-to-normal vision with contacts (no glasses were allowed). The data from two more were collected but excluded due to low eye-tracking locks.

Materials

Like the previous two experiments, stimuli consisted of 21 pictorial scenes adapted from Richland, et al. (2006). The images had the same qualities as those used in the previous studies, however they were shown one at a time, and were centered on a computer screen such that there was a black outline around them, totaling 1440 by 900 pixels in size.

Every image depicted two objects engaged in a primary relational activity (e.g., while a person chasing a dog might be described as a “behind” relationship, “chasing” was expected to be a more prominent relation in the scene; see Figure 13). Two experimenters coded and normed these images and 100% agreement was achieved for each stimulus.

There were two classifications of relations. First, key relations were chosen because they could be represented as binary relations and were amenable to one-word descriptions that differed depending on which object was bound to which role (i.e., which object was designated as the actor and which was designated as the patient). For example, *chasing(x,y)* might be described as *fleeing(y,x)*. These relations were depicted such that two of the image’s primary objects (the ones engaged in the primary relation) began equidistant from the center of the screen on the x-axis (see Figure 13). The full list of these relations can be found in Table 6). Second, filler items were chosen because they were also expressible as binary relations, but had a more prominent single relation (see Table 7). These relations were not depicted with the prominent relational items in the center of the screen. The goal here was simply to provide across-item variation with regard to item placement so as to control for spatial biases that might develop if every stimulus had two items in the same locations (e.g., “always look center left, then look center right because all items have allowed for this gaze pattern”).

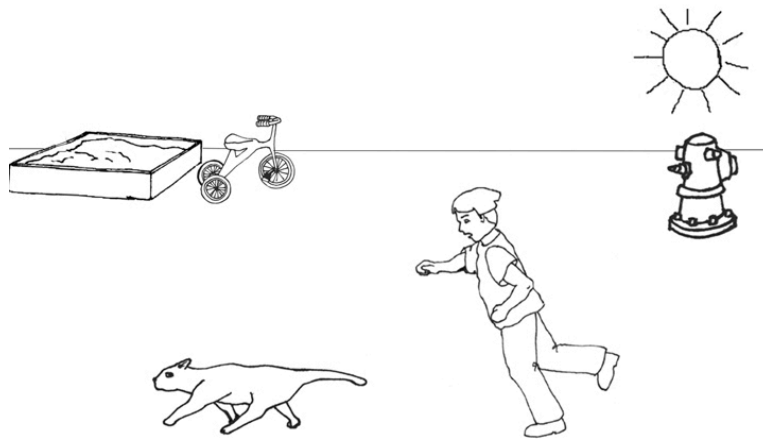


Figure 13: An example of a key stimulus in which the two relationally- engaged objects begin an equal distance away from the image-center.

Table 6: Key relations used in Experiments 4A and 4B. Each relation afforded multiple relational descriptions.

Possible Relation Description 1	Possible Relational Description 2	Objects Used In Stimuli
Chasing	Escaping	boy, cat
Talking	Listening	woman1, woman2
Lifting	Hanging	woman, monkey
Hunting	Escaping	man, elephant
Kicking	Cowering	boy, dog
Showing	Watching	boy, woman
Dropping	Falling	woman, baby
Pulling	Riding	boy, dog
Eating	Feeding	mother, child
Pushing	Riding	girl, boy

Stimuli were presented in a random order using the Pygame module (a Python-based gaming module). Pygame was interfaced with an EyeLink II (i.e., a binocular eye-tracker made by SR Research) to collect ocular fixations and saccades. Each stimulus had a small text-box below it so that participants could enter an answer by typing it in and then pressing “Enter”. Possible spatial biases were controlled by flipping the images on their horizontal axes across participants. Thus, half of the participants saw one item on the right hand side of the screen, while the other half saw that same item on the left.

Table 7: A list of filler items used in Experiment 4A

Primary Relation	Objects Used In Stimuli
Brushing	girl, hair
Cooking	man, food
Fighting	boy1, boy2
Hoisting	girl, monkey
Kissing	girl, dog
Opening	girl, gift
Pouring	boy, water
Reaching	man, baby
Scolding	woman, girl
Towing	tow-truck, car

Design

The experiment began with eye-tracker calibration. For this process, each participant was fitted with the head-mounted eye-tracker so that it was securely fastened. They sat approximately 36 inches from a 24-inch flat panel LCD monitor. Cameras were adjusted and focused, and the thresholds for detecting pupils were automatically calibrated. This allowed the experimenter to ensure that the track was not lost at any

location on the screen. A nine-point calibration was performed before validation, which ensured that there were no tracking errors. If validation showed minimal error, then the experiment began.

Participants were then told (both verbally and in text) that they needed to type the relational verb that they thought was most prominently depicted in each picture. A single training trial was then given. It began with a fixation cross that was shown for 1000ms, was white, and was centered on screen. A relational image was then shown, which depicted a “playing-with” verb, but was otherwise the same as the rest of the stimuli. Participants were told to type an answer, and then shown their own answer with the possible candidate answer of “playing-with”. Both were shown so to ensure that they understood what a relational verb was. Instructions were then reiterated.

Participants then began the experiment. They worked, self-paced, through all problems (no further instructions were given). Drift-corrects were taken every 5 trials to ensure that the eye-tracking lock was maintained (which is simply a shorter version of the initial calibration phase).

Results

Two measures were collected. First, we analyzed participants’ responses. These were in the form of words, and coded based on which object was bound to the actor role (for example, “chasing” would designate the boy in Figure 3 as the actor). For the sake of calculations, one relation was chosen as the default for each image (in every case this default was the relation listed in the first column of Table 1), and responses were coded as 1 for “actor-based” or 0 for “patient-based” in reference to that “default” relation. So, for example, “chasing” was considered the default for one image, and so a “chasing” response was coded as “actor-based”, while “escaping” was coded as “patient-based”.

Given that this experiment was exploratory, and that we wanted to determine whether there is a correlation between looking at an item and recognizing a relation where that item is the actor, we had a number of exclusion criteria. First, any non-verb responses were eliminated (e.g., “friendship”) since such answers showed a lack of understanding with regard to the task. Likewise, any responses that were either non-relational (e.g., “running”) or unclear with regard to which object was the actor (e.g., “playing”) were eliminated. It is interesting to note that, despite the open nature of the responses, there was a high degree of commonality across answers. For example, for one stimulus “feeding” was provided 44 times, and “eating” was provided 6 times—no other answers were given. Likewise, another stimulus was described as “kicking” in 53 out of 54 valid responses. This result suggests that each image had a “dominant” relation to participants.

Second, visual attention was tracked. We were specifically interested in the first item of fixation, which was operationalized as the first object within an image’s primary relation that was fixated upon. Analysis began by specifying square “areas of interest” around each object, and then checked whether a fixation was within that area. Like in the case of participant responses, fixations were coded as being “actor-” or “patient-oriented”.

Overall, 352 (approximately 72.43%) of responses matched the item of first

fixation (while 134, or approximately 27.57%, did not). However, because this was a repeated measures design, we used mixed effects logistic regression (see Jager, 2008) to further interpret these results. For this analysis, assuming a dominant relation (the first column of Table 8 was used for this purpose) the actor/patient orientation of the participants' response was treated as the criterion variable, while the first fixation was treated as a predictor. Given that this experiment used a repeated-measures design, Participant ID and Image ID were also included in the model as random factors. The model is described in Table 8, and a likelihood ratio test was used to compare it to a null model; it was found that first fixation made a significant difference ($\chi(1)=3.926, p<.05$).

Table 8: The model results from the experiment presented in Chapter 6.

Predictor	Coef (β)	SE(β)	z	p	Odds Ratio
Intercept	2.1000	0.8983	2.338	0.0194	8.165783
First Fixation	0.7015	0.3310	2.120	0.0340	2.016787

Discussion

The results of this study suggest that there exists a relationship between the item that one fixates on first and the item that one designates as a relational actor. As a result, they suggest that fixation is somehow related to the relation that is recognized. However, this study was correlational in nature, and so the following experiment attempted to direct visual attention to different objects in order to determine whether this relationship is also causal.

Experiment B

The objective of this experiment was to determine whether the trajectory of relational recognition may be manipulated by visual attention. Specifically, in light of the results of Experiment A, it will test whether priming the first item of fixation can change what relation is identified. The experiment will be almost identical to Experiment 4A, however, it will direct visual attention towards a specific object in each scene at the beginning of every trial.

Participants

Participants were 132 University of California Merced undergraduates that were otherwise similar to those used in Experiment A. Four participants were eliminated entirely due to poor eye-tracking locks.

Materials

The materials were the same as those listed in Experiment 4A with one addition. Priming was achieved by exploiting the eye-tracker's normal calibration process. Specifically, calibration involved a series of 15-pixel black dots with a 12-pixel white center point that appeared in various places around the screen. It required participants to fixate on the center of those dots and to press "spacebar". Thus, key trials involved two extra "calibration dots": one just before an image was shown, and then one 100 to 500 ms after the image appeared (the exact amount of time was randomly generated). The extra "dots" would appear at the central point of the object being primed, just prior to its presentation. A random number of filler trials also had extra "calibration" dots, but the locations of the dots were randomly generated and scattered across the screen.

Design

This experiment proceeded in almost the same way as Experiment A. However, during initial calibration the experimenter emphasized that she was having trouble getting a lock on the participant and so extra calibration throughout the study might be required.

Two controls were used: First, like in Experiment 1, images were flipped on their horizontal axes for half of the participants. Second, each relationally relevant item was primed for half of the participants (i.e., visual attention was drawn to that object just prior to it being presented). So, for example, if a trial depicted *chases*(boy, cat) (or *fleeing*(cat,boy)), then half of the participants were primed to initially fixate on the boy, while the other half were primed to initially fixate on the cat.

Results

Once again, participant responses and first fixations were tracked. However, the coding system for the responses changed slightly due to the research question. To the point, our goal was to determine whether making someone fixate on a specific object would change the relation given. Thus, we allowed for neutral responses in this experiment (and not just actor or patient based ones, like in the previous experiment). For example, "conversing" was allowed for the "talking" stimulus, despite the fact that conversing is a bidirectional relation. This approach seemed especially warranted given that the data from the first experiment indicated that most stimuli had a dominant relation that was recognized by most participants (i.e., one object that was typically bound to the actor role), and so looking for deviations seemed worthwhile.

First fixations were tracked and used to eliminate participants. Again, given that our research question was whether changing participants' first fixations would change the course of the recognition process, we used fixations to ensure that participants actually fixated on the prime. Trials in which a participant initially fixated on a different object were eliminated; this included 3% of all trials.

A mixed multinomial logistic model was used to interpret the results. Once again, participants' answers were treated as the criterion variable, while the prime was treated as the predictor, and Participant and Image IDs were treated as random factors. See Table 9, for the likelihood ratio test comparing the model to null showed that priming was a

significant factor ($\chi(1)=35.343$, $p<.01$). Specifically, it showed (again, by odds ratio) that one is 4.25 times more likely to recognize a relation that uses the primed item as an actor.

Table 9: The model results from Experiment 4B

Predictor	Coef (β)	SE(β)	z	p	Odds Ratio
Intercept	2.0807	0.8663	2.430	0.0151	8.010303
First Fixation	1.4462	0.2477	5.839	<.0001	4.246898

Discussion

The results of this study suggest that it is possible to shape relational recognition by manipulating which item is fixated on first. Thus, the relationship between first fixation and relational recognition is not just correlational, but causal. This result also suggests that attention, free of specific task-relevant movement, is capable of priming relational cognition. Thus, while we cannot be sure that representational priming can change the course of relational reasoning, it does appear that attentional priming may.

This finding also has implications for debates about mental representation, especially with regard to how relations are represented. It was pointed out earlier that DORA (and LISA) are somewhat unique in their use of role-filler bindings and time to create structured representations of relations⁶. The results presented here support this type of sequential processing over a holistic representation alternative. The data also notably extend this account beyond the simple spatial relations used by Franconeri et al. (2012) and suggest that this sort of processing might be true on a more global scale (i.e., it might be true for all relations, and not just spatial ones).

That said, there are some limits to the mechanistic explanation available at this point. First, Franconeri et al., (2012) specified the importance of saccades, while other work (e.g., Gleitman et al., 2007) and the current work specified the importance of early fixations. While both saccades and fixations can operationalize visual attention, saccades rely on movement to a greater degree. More work should be dedicated to determining how relational priming interacts with these different types of visual attention.

Second, this experiment only required relational recognition (no structure was manipulated, nor mappings completed). As a result, it is possible to conclude that visual attentional priming may affect relational recognition, but it cannot directly affect any other step in the reasoning process. Presumably, since recognition is a prerequisite for relational reasoning (Livins & Doumas, 2014) any performance bump from recognition might make its way through the rest of the process, however future research will need to determine whether this is the case.

⁶ Shastri and Ajjanagade's (1993) model, SHRUTI, is similar in that it uses role bindings and temporal synchrony. However, this model uses localist representations to represent concepts and objects, and therefore has been subject to the same critiques as many of the more traditional symbolic models (see Hummel & Holyoak, 1997).

Ultimately, the results presented here begin to outline the importance of visual attention in relational priming, and while they do not complete this account, they do provide a strong platform for a theoretical discussion of relational priming. Such a discussion is the focus of Chapter 7.

Chapter 7

Discussion

This project has covered significant ground. Its most general goal has been to provide a better understanding of relational reasoning and the processes that guide it. Early in this document, I pointed out that while relational reasoning is important and reasonably well understood in a functional sense, the field struggles to describe why the reasoning process takes one trajectory over another (e.g., why people prefer relational mappings, as described in Gentner 1988, yet often fail to reason relationally, as described in Gick & Holyoak, 1980 and 1983). I argued that priming could be one way of answering this question because it could provide a way of making relational reasoning more likely, and of altering its course.

This dissertation is founded on the expectation that if this hypothesis is correct, then whatever the priming mechanism is will be an important part of relational cognition. It was also founded on the observation that the existing work on relational priming is contentious, and sometimes there are reports of contradictory findings (as was the case in Spellman et al., 2001 and Bassok et al., 2008). In other words, it provides no meaningful explanation of such a mechanism. I argued that at least three questions need to be asked in order to address this issue: 1) *Is relational priming possible?* 2) *To what extent is it possible?* And 3) *how might it work?* The rest of this project was then dedicated to addressing each of these questions in turn.

At this point, the answer to Question 1 simply seems to be “yes”: the existing literature is filled with examples where priming had lingering impacts on reasoning about relational tasks, and this project was able to confirm such effects by way of visuospatial manipulations. In the context of this project, these effects were seen not only with regard to simple, obviously spatial relations (such as *above* and *below*, as seen in Chapter 3), but also with more complex relational verbs (such as *chasing* and *climbing*, as seen in Chapter 4).

The data from Chapters 3 and 4 also speak to Question 2. The data showed that relational priming can have significant effects even when the prime is relatively subtle and not task-relevant. As a result, it seems possible to conclude that priming can occur essentially automatically. This result is congruent with a selection of the relational priming literature (e.g., Bassok et al., 2008) and a wealth of embodied cognition research (e.g., Richardson et al., 2003; Pedone et al., 2001; Grant and Spivey, 2003).

That said, Chapters 3 and 4 did not *sufficiently* answer Question 2 (they are insufficient for providing an explanation of the conditions under which priming is automatic). Thus, I proceeded to investigate the mechanisms underlying relational priming more explicitly. I took a cue from the work on relational representation and the corresponding computational accounts, and argued that the DORA model (Doumas et al., 2008) provides not only a reasonable account of relational reasoning, but also two possible priming mechanisms that could be investigated experimentally: *Content-based priming*, and *attention-based priming*. As previously discussed, the former may function to directly activate some set of relational features (say, a horizontal image schema in the case of *chasing*), while the latter may produce some bias that causes one to move one’s eyes differently around a scene, thereby heightening the probability of noticing one

relation over another. While both may ultimately result in the activation of a given relation, the process by which that activation occurs differs between them.

Chapter 5 offered an experimental investigation of these two candidate mechanisms. Here, I used stimuli that decoupled content-based priming from attentional priming and found that attentional priming produced a significant effect over the content-based priming. I did, however, achieve priming through a combination of attention and movement, which leaves an open question about the role of movement itself in relational priming. As a result, I further explored the role of attention in Chapter 6 by priming it without also priming movement. Here, a stationary dot-prime captured attention and directed it towards a particular object that played a particular relational role, and it was found that such a prime was sufficient to affect relational recognition (i.e., which relation was recognized in a scene). As a result, it appears that attention-based priming is sufficient for relational priming in the absence of both content- and movement-based cues.

Ultimately then, attention seems to be a crucial mechanism for relational priming, and therefore for relational cognition as a whole. It appears that the way in which we attend to a problem affects the relation that gets recognized, along with the overall trajectory of reasoning about that relation.

This claim has a number of implications. First, it may be important to look back at existing literature through the lens of this work. Many (if not all) of the relational priming studies might be explainable in terms of attention-based priming. In some cases this explanation is simple, as in the case of Spellman et al. (2001), who found that priming could not be achieved unless participants were directed to pay attention to relations and to relations between relations. In other cases it might take the consideration of possible demand characteristics. For example, Bassok et al., (2008) reported an automatic priming effect when semantically aligned word pairs were paired with addition problems. One might argue that this effect relied on some semantic activation of “going together” or “addition”, however Bassok et al. acknowledged that their methodology may have created a context that drew attention to relational similarities. As shown in Figure 14 (taken from Bassok et al., 2008), they placed each word directly below a digit, and placed an addition sign between them. This alignment could draw attention to the symbolic nature of addition, and so while the experimenters did not intend to direct attention, they might have done so implicitly.

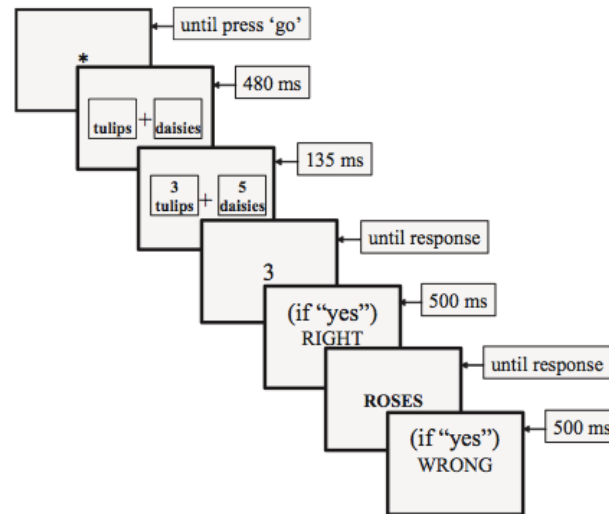


Figure 14: A figure taken from Bassok et al., 2008 showing their stimuli. Notice that the numbers appear just above words with an addition sign in between.

Second, more research must be done on the interactions between relational reasoning and sensory-motor/attentional processing. Consider the fact that many relations will be learned and experienced across exemplars displaying consistent alignments (e.g., all instances of *above* will involve a vertical alignment because of that alignment is part of its very definition). In such cases, attention might prime a response in at least three different ways. First, it might make one more likely to move one's eyes in a particular way, thereby making it easier to notice a congruently aligned relation. However, directing attention such that one might be more likely to notice a relation *might* also cause that relation's content (i.e. features) to become more active in congruent cases. Finally, it *might* also prime a particular strategy or way of approaching a problem. While this possibility has not been explored within the domain of relational cognition (neither in this project nor the greater body of literature), Ratcliff and McKoon (1981) studied it with regards to word recognition. They found that priming effects were sometimes scaled with the probability of the prime being task-relevant (particularly at longer time scales), and so argued that the priming could be attributed to strategic processes. Ultimately, the data here cannot discern which of these explanations might be the case, nor under what circumstances each one might be possible. As a result, future work will need to explore exactly how attention interacts with a robust set of cognitive processes in order to fully describe the mechanisms of relational priming.

Third, such explanations will need to be mobilized to answer the bigger questions about relational cognition that the field has been wrestling with. For example, relational recognition has only recently been brought up as a discussion point (see Livins & Doumas 2014). This research suggests that it needs to be a bigger discussion point, and that visual attention might be a key part of how relational recognition proceeds. As a result, there may be an even bigger need to expand current relational models to account for both recognition and attention. For example, while models like DORA rely on featural consistencies that are noticed across exemplars to learn and encode a relation's representation, it is unclear in the model as to how those consistencies are noticed in the first place. Given the impact of those consistencies on the model throughout the

reasoning process, accounting for their recognition may produce a more accurate and complete model.

Finally, the interactions between low-level sensory-motor processing (like vision) and high-level reasoning (like analogy) will need to be expanded overall. To date, minimal work (either experimental or computational) has been dedicated to explicating the relationship between the two, though this project demonstrates that subtle visual and spatial manipulations can have big impacts on how people solve complex problems. At minimum, it seems that there are functional links between the two, and the data presented here may indicate that attention is a link between them. Describing those links will not be simple, but future work will need to develop them.

That said, the current research is sufficient to provide fruitful avenues for future applied research. For example, math-learning researchers have recently become interested in how to promote the coordination of multiple representations during problem-solving (e.g., how students may map a graph to an equation). Such tasks (like many mathematical problems) are inherently relational (Landy & Goldstone, 2007; Russel, 1918), and work has begun to determine that attention is important for the process. For example, Wills, Shipley, Chang, Cromley, & Booth (2014) showed that one's tendency to gaze at particular elements in the representations may predict one's ability to coordinate across them. In light of the data presented in this project, it seems that directing attention to such elements might actually have positive learning/reasoning outcomes. Likewise, this insight could be important for developing math-learning technologies that harness sensory-motor/spatial cues, such as *Graspable Math* (Ottmar, Landy, & Goldstone, 2012). Given that such technologies may direct attention, visual perception, and movement around a problem-space, it might be especially crucial to remain considerate of how the user may interface with the program in order to prime correct performance while simultaneously avoiding priming poor performance.

Ultimately, while this project answers a number of questions about relational priming, it is also a beginning. First, it is a beginning to linking relational priming to attention—a process not previously explicitly linked to relational reasoning. By extension, it is also a beginning to understanding relational priming in a more complete and functional way. And of course, it is a beginning to establishing a meaningful link between relational priming and visuospatial processing—another process that has been ignored by many relational reasoning researchers up to this point. Of course open questions remain, but these beginnings can not only start the field on a road to creating a more complete account of relational priming, but also to understanding why controversy exists in the current literature and how it might reconciled. In summation, this project demonstrates that while analogy might be the “core of cognition”, it is highly interconnected with, and shaped by, a multitude of other processes and sensory-motor mechanisms.

Appendix A

Task Instructions For Experiment 1

We're going to play a game! In a moment you are going to see two shapes at a time. Each pair of shapes will be positioned according to a rule. We're not going to tell you what the positioning rule is though - the game is that you have to figure it out!

Here's how you play: If you think a pair of shapes follows the positioning rule, press the A key. If you think the pair doesn't follow the positioning rule, press the B key. We will give you feedback each time you press A or B to help you figure out what the positioning rule is.

Here are some hints to help you: The positioning rule has to do with the relationship between the shapes of each pair. Also, there is only one rule, and every pair will either follow it or not. You win the game when you figure out what the positioning rule is and demonstrate your ability to correctly identify whether a pair follows it or not!

Good luck!

Appendix B

Time's Effects On Analogical Crossmapping Performance

This experiment had almost the same design as the experiment found in Chapter 3, however it did not involve priming. Thus, in this experiment I studied the effects of time pressure on relational reasoning by using crossmapping analogy problems. The experiment involved simultaneously showing participants the base and target analogs, but removing the base after varying amounts of time. Thus, conditions were defined by those presentation times. The performance variable of interest was the number of relational mappings made over the number of featural mappings, by condition.

Participants:

Participants included 90 undergraduate students from the University of California, Merced. They were recruited through a participant pool and received course credit for participation. All participants had normal to corrected-to-normal vision.

Data from 4 of those participants were collected but excluded. In two cases the exclusion was due to the participant's phone ringing during participation, another was due to the participant's admitted misunderstanding of the task after experiment completion, and in the final case it was due to loud, unexpected construction taking place in the hallway outside of the laboratory during participation.

Stimuli:

Stimuli consisted of pictorial scenes adapted from Richland et al., (2006). Each contained six objects dispersed around a black and white, drawn image; all were 720-by-450 pixels in size and included both living and non-living things. They were presented on a 1140-by-900 pixel screen, so the stimuli were centered and then shown on a black background.

Each scene depicted one of the following relations: *chasing, kissing, scolding, dropping, reaching, pulling, hunting, hanging, balancing, or towing*. Each relation was used in three different problems, and was depicted twice for each problem. Fourteen problems were crossmappings, where one identical object was depicted in the base and the target analogs. Another sixteen problems were fillers that had unique objects in the base and the target. Every problem was presented with the base analog in the top half of the screen, with one item circled in red. The target analog was always presented directly below the base, with four items enumerated in red. In key trials, a featural and a relational match were both enumerated (see Figure 6 in Chapter 4 text).

Design:

Time pressure was achieved by removing the base analog after 500 ms, 750 ms, 1000 ms, 1250 ms, or 1500 ms. The presentation times were treated as conditions, and each participant was only exposed to one, creating a between-subjects design. Thus, participants were initially randomly assigned to one of these conditions.

The experiment began by seating participants in front of the computer. They were told to “find the thing doing the same thing” in the bottom image as was circled in the top image, and to answer by pressing the number key corresponding to that item in the target. They then completed one training trial. It began with a 500 ms presentation of a fixation cross, centered in the screen. Both analogs were then shown, and the base removed after one of the specified amounts of time. The target remained on screen until the participant entered an answer. This trial involved one extra problem involving a *feeding* relationship, after which the experimenter repeated the task instructions and answered any procedural questions (i.e., she would answer questions like “So I press the number I think is the answer?” but not “Was that the right answer?”). Participants then completed the rest of the experiment self-paced.

Results:

Answers for key trials were used for analysis, and two analyses were completed. First, the overall number of problems that were answered relationally was calculated. A one-way ANOVA showed an overall difference between time steps ($F(4, 82)=4.290$, $p<.01$), and Bonferroni post-hoc tests showed significant differences between the 500ms condition and the 1250ms condition ($M=5.42$, $SD=2.71$, and $M=8.17$, $SD=2.87$, $p<.01$), and the 1500ms condition ($M=8.73$, $SD=2.55$, $p<.05$; see Table 10 and Figure 15).

Table 10: Results of the current experiment. It shows the number of relational mappings by temporal presentation of the base analog.

Condition	Mean Performance	SD
500	5.42 (38.7%)	2.71
750	6.17 (44.07%)	2.64
1000	7.76 (55.42%)	3.27
1250	8.17 (58.36%)	2.87
1500	8.73 (62.36%)	2.55

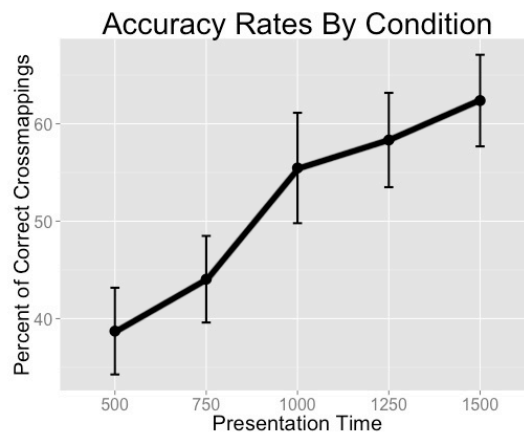


Figure 15: A graphical representation of the results from the experiment presented in Appendix B. The presentation time is shown on the x-axis, and the percent of relational mappings is shown on the y-axis. Error bars represent the Standard Errors.

Second, the number of featural responses was calculated (i.e., the number of questions that participants answered with the identical object match). A one-way ANOVA showed a significant difference by time-step ($F(4,82)=4.852, p<.01$), and Bonferroni post-hoc tests showed significant differences between the 500 ms condition and the 1000 ms condition ($M=6.89, SD=2.77$, and $M=4.25, SD=2.47, p<.05$), the 1250ms condition ($M=3.94, SD=2.34, p<.01$), and the 1500ms condition ($M=3.73, SD=2.02, p<.01$; see Table 11 and Figure 3).

Table 11: Results of the experiment presented in Appendix B. It shows the number of featural mappings by temporal presentation of the base analog.

Condition	Mean Performance	SD
500	6.89 (29.21%)	2.77
750	5.78 (41.29%)	3.12
1000	4.35 (31.07%)	2.47
1250	3.94 (28.14%)	2.34
1500	3.73 (26.64%)	2.02

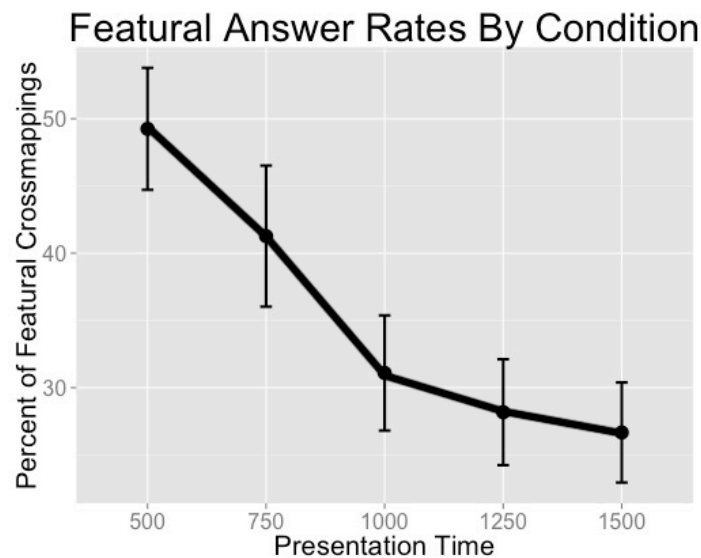


Figure 16: A graphical representation of the results from the experiment presented in Appendix B. The presentation time is shown on the x-axis, and the percent of featural mappings is shown on the y-axis. Error bars represent the Standard Errors.

Discussion:

The data suggest that time pressure does affect the chance of answering a crossmapping problem with a relational mapping whilst under time pressure, and that the pressure makes it significantly more likely that one will select a featural mapping.

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