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Analogical Transfer From a Simulated Physical System

Samuel B. Day and Robert L. Goldstone
Indiana University

Previous research has consistently found that spontaneous analogical transfer is strongly tied to concrete and contextual similarities between the cases. However, that work has largely failed to acknowledge that the relevant factor in transfer is the similarity between individuals' mental representations of the situations rather than the overt similarities between the cases themselves. Across several studies, we found that participants were able to transfer strategies learned from a perceptually concrete simulation of a physical system to a task with very dissimilar content and appearance. This transfer was reflected in better performance on the transfer task when its underlying dynamics were consistent rather than inconsistent with the preceding training task. Our data indicate that transfer in these tasks relies on the perceptual and spatial nature of the training task but does not depend on direct interaction with the system, with participants performing equally well after simply observing the concrete simulation. We argue that participants generated a spatial, dynamic, and force-based mental model while interacting with the training simulation and tended to spontaneously interpret the transfer task according to this primed model. Unexpectedly, our data consistently show that transfer was independent of reported recognition of the analogy between tasks: Although such recognition was associated with better overall performance, it was not associated with better transfer (in terms of applying an appropriate strategy). Together, these findings suggest that analogical transfer between overtly dissimilar cases may be much more common—and much more relevant to our cognitive processing—than is generally assumed.

Keywords: analogy, transfer, mental models

Analogical reasoning is widely acknowledged as a powerful tool in human cognition (see e.g., Dunbar & Blanchette, 2001; Gentner, 1983; Hofstadter, 1996; Holyoak & Thagard, 1989; James, 1890). It allows an individual to see the commonalities between seemingly disparate situations by looking past simple surface details to focus instead on underlying relational structure—how the components of the systems fit together and relate to one another. In so doing, analogies allow a person to make structurally sound inferences about new situations, and they provide the opportunity to productively draw on one's wealth of existing knowledge (Gentner, Holyoak, & Kokinov, 2001).

However, research has repeatedly shown that people can have great difficulty taking advantage of this tool (see Detterman, 1993). In one classic example, Gick and Holyoak (1980) provided participants with a concrete example of a problem being solved using a convergence strategy, in which several small forces converge at a single location and sum to produce a large effect. When the participants were subsequently asked to solve an analogous problem from a different domain, however, they were unlikely to spontaneously recognize the relevance of the prior example, and they failed to transfer the appropriate solution strategy. The difficulty was not with the soundness of the analogy itself—when given a hint to think about the prior example, participants were quite good at making use of the relevant strategy. Rather, the problem seemed to be their inability to spontaneously see the connection between the two episodes. This general pattern has been found numerous times (see e.g., Hayes & Simon, 1977; Perfetto, Bransford, & Franks, 1983; Reed, Ernst, & Banerji, 1974; Weisberg, DiCamillo, & Phillips, 1978). Given this conspicuous gap between the great potential of analogical reasoning and its apparent inaccessibility in relevant situations, a significant amount of research has explored the factors that influence analogical reminding and use.

Arguably the most important such factor is the concrete content of the episodes themselves. Research on analogical transfer distinguishes between the "deep," abstract, structural aspects of an episode and the superficial "surface" content, which includes the concrete, domain-specific details of a particular example. For instance, in Rutherford's classic model of the atom based on an analogy with the solar system (see Gentner, 1983; Hesse, 1966), the abstract structure of multiple entities that revolve around a more massive core is relevant for meaningful transfer, whereas details such as the color and the temperature of the sun are considered irrelevant (and potentially distracting) surface features. Research has shown that such concrete features may often be an impediment to transfer.

For instance, people are unlikely to notice that a new situation is structurally similar to a previously known case if their surface features are dissimilar (see e.g., Gentner, Ratterman, & Forbus, 1993; Holyoak & Koh, 1987; Ross, 1984; though see Wharton et

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Samuel B. Day and Robert L. Goldstone, Department of Psychological and Brain Sciences, Indiana University.

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Correspondence concerning this article should be addressed to Samuel B. Day, Department of Psychological and Brain Sciences, Indiana University, 1101 East 10th Street, Bloomington, IN 47405. E-mail: day9@indiana.edu

al., 1994). In fact, even when two situations share concretely similar entities, transfer can still be greatly impaired (or even "negative," with performance below controls) if those entities are mismatched in the roles that they play in their respective cases (so-called cross-mapping; see e.g., Gentner & Toupin, 1986; Ross, 1987). Furthermore, this kind of interference is exacerbated when the relevant entities are "richer" and more concretely detailed (see e.g., Markman & Gentner, 1993; Ratterman & Gentner, 1998).

Consistent with findings such as these, there is evidence that reminding and transfer may be facilitated when the concrete content of the cases is reduced. For example, Clement, Mawby, and Giles (1994) found that analogical retrieval was improved substantially when the situations were described in domain-general terms rather than more concrete and specific language. Similarly, Goldstone and Sakamoto (2003) found better transfer among poor learners when entities in a training task were more idealized perceptually (also see Kaminski, Sloutsky, & Heckler, 2008; Uttal, Liu, & DeLoache, 1999). The benefits of idealization apply to mental representations as well as the situations themselves. For instance, factors that have been positively linked to increased structural reminding, such as expertise (see e.g., Novick, 1988; also see Chi, Feltovich, & Glaser, 1981) and comparison of multiple cases (see e.g., Gentner, Loewenstein, & Thompson, 2003; Gick & Holyoak, 1983), are thought to result from the development of more abstract cognitive representations.

This last point is critical to bear in mind. The concreteness of the actual situations matters only indirectly; it is the concreteness of one's mental representations that is relevant for transfer. For instance, an expert in physics may be able to recognize commonalities between overtly dissimilar cases because she is able to represent them in a way that highlights the relevant principles of force and motion and minimizes irrelevant perceptual features (see e.g., Chi et al., 1981).

Although improvements resulting from increasingly abstract mental representations have been widely considered, the focus of our studies is a different way in which mental representations may overcome surface dissimilarities between cases. Specifically, two situations may become subjectively more similar because of concrete similarities in the mental models that are used to represent them.

Mental Models

There is considerable evidence that people are likely to reason about complex real-world systems by using *mental models*, or simplified structured representations of those systems (Gentner & Stevens, 1983; Hegarty, 2004; Nersessian, 1999, somewhat distinct from Johnson-Laird's, 1983, formulation). By defining qualitative relationships within a system, these models describe influences between parts and promote inferences about the system's operation. In some cases, such models are a fairly literal translation of the represented situations themselves, such as reasoning about a system of pulleys through a mental simulation of those pulleys (see e.g., Hegarty, 1992). At other times, however, people appear to reason about more complex or abstract domains through the use of isomorphic physical systems (see e.g., Gentner & Stevens, 1983; Kempton, 1986). For example, Gentner and Gentner (1983) found that students were likely to understand electrical currents through analogies to the flow of water or the movement of crowds of people. By reasoning via analogy to these familiar systems, individuals were able to take advantage of the intuitive causal relationships between physical objects in order to understand more complex or less transparent situations. Similar conclusions have been reached in research on naïve physics (Talmy, 1988; Wolff, 2007) and embodied cognition (see Barsalou, 2008; Gibbs, 2006, for recent reviews).

The current experiments explore the possibility that transfer may occur between even highly dissimilar tasks when individuals' mental representations of those tasks are, in fact, concretely similar. Specifically, we predicted improvement on a fairly complex and difficult-to-understand task when it was preceded by an (overtly dissimilar) intuitive physical system that could serve as the basis for an appropriate mental model for the transfer task. Of course, it is impossible to precisely specify the contents of participants' mental models, but we would argue that an effective model in these cases would include analog, spatial representations of the system but also explicit representations of less directly perceptual information, such as temporal and causal relationships, and the dynamics of interacting forces. By varying aspects of our training task in the current studies, we try to assess the influence of factors such as these.

It should be noted that our transfer task differs in some important ways from those generally used in previous studies, which frequently involve the transfer of discrete insight solutions between text passages. Instead, our task involves interaction with a dynamic system in service of achieving a specific goal. In addition to being at least as ecologically valid as the more traditional methods, participants' solution times should provide a more sensitive measure of transfer than simple success or failure.

Some recent findings are consistent with our predictions, although the theoretical questions in those studies were different. Pedone, Hummel, and Holyoak (2001) found that transfer performance was greatly improved when participants were shown dynamic animations of a convergence schema prior to a task in which convergence was the relevant transfer principle. Although stating that there were many possible explanations for this finding, the authors noted the importance of concrete, perceptual representations in deeply understanding such a schema. In another study (Catrambone, Craig, & Nersessian, 2006), participants who "acted out" a written story by moving wooden blocks on a table showed much higher rates of transfer than did others, who recreated the story either verbally or through sketches.

These results are consistent with the claim that seemingly far transfer may occur if the training task provides the basis for an effective mental model of the transfer task. However, the experiments in those studies were not explicitly designed to assess that possibility and are open to alternative interpretations. In addition to exploring aspects of this prediction much more directly and systematically, the current studies provide stronger control conditions by using materials that are perceptually identical between conditions.

Explicit Versus Implicit Representations

One important issue that arose in the course of the current investigation is the role of explicit awareness in the observed transfer effects. There are many reasons to predict that transfer under the presented conditions would strongly rely on participants' explicit, verbalizable knowledge of the structural commonalities between the tasks. For example, it has repeatedly been found that providing participants with an explicit hint to think about a relevant previous situation when approaching a new task can greatly increase transfer (see e.g., Gick & Holyoak, 1983; Novick & Holyoak, 1991). In fact, a fair amount of research on analogical transfer has used explicit reminding of previous cases as a dependent measure (see e.g., Gentner et al., 1993). More generally, many have argued that explicit declarative memory is a necessary requirement for any flexible application of knowledge (see e.g., Cohen, Poldrack, & Eichenbaum, 1997; Reber, Knowlton, & Squire, 1996), of which analogical reasoning is a prototypical example.

On the other hand, there have been a few specific examples in the literature of apparently implicit application of structural knowledge across different kinds of cases (see e.g., Brooks & Vokey, 1991; Day & Gentner, 2007; Gross & Greene, 2007; Schunn & Dunbar, 1996). Furthermore, the procedural nature of our transfer task might lend itself to more implicit kinds of processing. Numerous studies have found evidence for implicit learning of both motoric (see e.g., Milner, Corkin, & Teuber, 1968) and more strictly cognitive (see e.g., Cohen & Squire, 1980) procedures. It should be noted, however, that the procedural knowledge in those studies was learned and applied in exactly the same task, in contrast to the highly dissimilar training and transfer tasks in the current studies. Furthermore, recent research has increasingly called into question the very idea of implicit memory (see e.g., Shanks, 2005). These issues are discussed further in the course of interpreting our results.

Experiments

All participants first interacted with a computer simulation involving the oscillating motion of a ball that was suspended between two elastic bands. Although the general operations of this system were consistent with participants' naïve physical theories, the actual strategies necessary to elicit a desired behavior from the system were often less than intuitive and generally required a fair amount of trial and error. Next, all individuals participated in an ostensibly unrelated task, which involved regulating the population of a city. Although this second simulation differed considerably from the first in terms of its content and visual display, the system was in fact governed by the same underlying principles, mathematical equations, and force-based dynamics as was the ball task.

In both simulations, participants were asked to accomplish a specific goal, which required the development of an appropriate strategy. Our primary manipulation was in the relationship between the goals for the two tasks. For some participants, the two goals were analogous and thus required analogous strategies to achieve. For other participants, the two goals were structurally dissimilar, with each requiring a unique (contrasting) strategy. If participants were in fact able to transfer their learning from the interaction with the concrete, spatially explicit system to the dissimilar and less spatial population task, we would expect facilitation for those participants with consistent, analogous goals.

Obviously, the actual domains in both of our tasks are physical. However, in the ball simulation, the spatial and mechanical information that is relevant to completing the task is instantiated directly and literally. By contrast, in the transfer population task, the relevant information is in terms of numerical quantities rather than physical space, and the interacting "forces" are societal rather than mechanical. We suggest, however, that an effective cognitive representation for the transfer task is a mental model that is much like the consistent version of the ball task, with the population variables construed in terms of an isomorphic physical system. If so, we might expect transfer between the two cases, because cognitively the tasks are represented quite similarly (in the analogous condition).

Experiment 1a

Method.

Participants. Sixty-three Indiana University undergraduates participated in this study for partial course credit.

Materials and design. All participants were presented with two tasks. In the first task, participants interacted with a simulation of a physical system, a ball that was suspended between two elastic bands that were attached on either side of the ball. The bands stretched horizontally in either direction, and each was attached to a stationary pin. As discussed shortly, a fan was located to the left side of the ball system (see Figure 1). The motion of the ball was fairly realistic and was easy to grasp intuitively. Greater distance from either pin led to more stretching of the band and greater force pulling toward that pin. Computationally, the ball moved according to simple physical rules—its natural tendency was to continue at a constant speed and direction, which could be altered by forces from the two bands. This force increased as a function of the length of the bands, reflecting a stronger pull from each band as it was stretched farther. Thus, as the ball moved farther from either pin, there was an increase in the force pulling back toward that pin, eventually slowing the ball and pulling it back. Because there were two opposing forces (from the elastic band connecting to each of the two pins), the ball tended to oscillate: As the ball moved toward either pin, the force from the opposing band would increase and eventually pull it back. For simplicity's sake, neither gravity nor friction was included in the model.

Participants were first asked to take a few minutes to explore and familiarize themselves with the behavior of the system. Users were able to click on the ball and drag it to any position within the display (both horizontally and vertically) and then observe the motion that resulted when the ball was released. Participants proceeded at their own pace and were allowed to interact with the simulation for as long as they wished.

The experiment then proceeded to the training phase of the task. During this phase, participants were no longer able to interact with the ball directly. However, they were given a new way to manipulate its behavior: A fan was placed to the left of the system, blowing rightward across it (see Figure 1). When activated, this fan introduced a small additional force in the rightward direction,

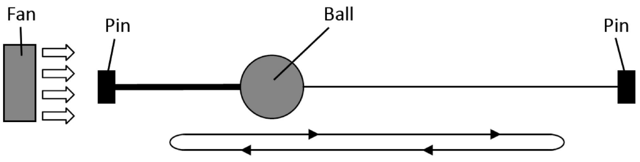


Figure 1. Schematic of the training (oscillating ball) task.

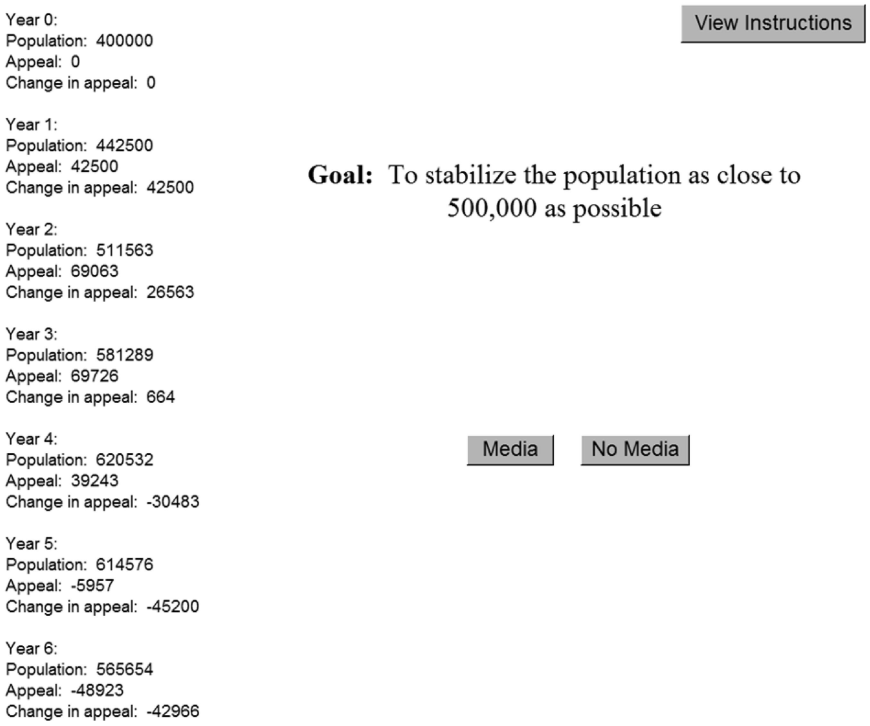
subtly altering the ball’s motion. In this phase, there were no vertical forces operating on the ball, so the ball’s path was always horizontal.

Each participant was asked to accomplish one of two goals: to cause the ball to reach the pin on the far right (the maximize condition) or to cause the ball to stop directly between the two pins (the stabilize condition). In other words, each participant needed to consistently increase or decrease the amplitude of the ball’s oscillations. In the described system, when the ball is traveling to the right, the force from the fan will add to its net velocity, causing it to travel slightly farther in that direction (and thus increasing its amplitude). When the ball is traveling to the left, however, the force from the fan will oppose its velocity, slowing the ball’s movement in that direction and thus decreasing its amplitude. Constant application of the fan would thus lead to no net change in the ball’s amplitude and would not help in achieving either goal. Both possible goals require working with “resonance,” by coordinating the force from the fan with the inherent frequency of the system. For example, when the task is to reach the far pin, the optimal strategy is to activate the fan only during the rightward part of its oscillation to increase its amplitude. Conversely, when the task is to stabilize the ball in the middle, the optimal strategy is to activate the fan only during the leftward part of its oscillation to decrease its amplitude. Participants were not informed of these strategies. (A Flash implementation of the basic ball task is available online at http://cognitrn.psych.indiana.edu/complexsims/Oscillatingball.html.)

Participants were required to complete their assigned task seven times. On average, the entire ball task (including familiarization) took just under 10 min. Participants were told, upon completion, to ask the experimenter to start the next, ostensibly unrelated part of the experimental session.

Participants were told that the next task involved a computer simulation of how a city’s population could vary over time and how it could be influenced by media advertisement. According to the instructions, the city in question was large enough to comfortably hold 500,000 residents. If there were fewer people, the city would become more attractive to outsiders because of abundant housing and low traffic congestion. With more than 500,000 residents, it would become less attractive because of crowding, crime, and expense. Thus, the city’s appeal would increase whenever the population was below this optimal level and would decrease when the population was above this ideal. Furthermore, instructions stated that the amount of the change in appeal would be greater as the distance from 500,000 increased. Unlike in the previous task, the interface for the population simulation was entirely textual and proceeded in discrete time steps rather than the real (continuous) time used in the ball task. At each time step, participants were given numeric values for the city’s population, its current appeal, and the change in its appeal from the previous time step (both the appeal and change in appeal could be positive or negative). This information was presented in a scrolling text display, which also allowed the information from the previous four steps to remain visible on the screen (see Figure 2).

Participants in this task were also given one of two goals to accomplish: either to cause the population to reach 1,000,000 or to cause the population to stabilize around its optimal value of 500,000. To achieve these goals, participants decided at each time step whether to introduce media advertisement, which would increase the city’s appeal for that one step. Participants were re-



Year 0:
Population: 400000
Appeal: 0
Change in appeal: 0

Year 1:
Population: 442500
Appeal: 42500
Change in appeal: 42500

Year 2:
Population: 511563
Appeal: 69063
Change in appeal: 26563

Year 3:
Population: 581289
Appeal: 69726
Change in appeal: 664

Year 4:
Population: 620532
Appeal: 39243
Change in appeal: -30483

Year 5:
Population: 614576
Appeal: -5957
Change in appeal: -45200

Year 6:
Population: 565654
Appeal: -48923
Change in appeal: -42966

Goal: To stabilize the population as close to 500,000 as possible

Figure 2. Display for the transfer (population) task.

quired to complete this task three times. Note that these goals (stabilizing and maximizing) are analogous to the two possible goals in the ball task.

Although the content and appearance of the first and second simulations were quite different, the principles governing their operation were essentially identical. The city's population is analogous to the position of the ball at a given point in time. The city's appeal, representing the numerical change in population from one step to the next, therefore maps onto the velocity of the ball. Similarly, change in appeal, describing the degree to which the change in population is increasing or decreasing, is analogous to acceleration. Finally, media investment plays the same role as the fan, allowing the participant to add a unidirectional force at any point in time. The behavior of the system is therefore formally and qualitatively the same as that of the ball simulation. The population tends to oscillate around the midpoint of 500,000, and adding media advertisement when the population is rising or falling will, respectively, increase or decrease the amplitude of this oscillation. The operation of both systems is governed by the formula

$$\text{Velocity}_{t+1} = \text{velocity}_t + [(\text{midpoint} - \text{position}) \times \text{constant}] + \text{optional user force}$$

Our primary interest for this study was in whether solution strategies acquired in the first simulation would transfer to the population task, which was overtly quite dissimilar. Specifically, we predicted that performance on the population task would be facilitated when the goals of the two tasks were mutually consistent (i.e., both had the goal of maximizing the amplitude or both had the goal of stabilizing the amplitude) rather than inconsistent (maximizing the ball's location and stabilizing the population or vice versa). The primary dependent variable was the number of time steps required to complete the population task (averaged across the three attempts), assessed in a 2 (goal consistency) × 2 (population task type) factorial design. Additionally, pilot data showed that participants found the population task was quite challenging and suggested that some participants may not be able to complete the task within the allotted hour of the experimental session. It may therefore also be informative to analyze the data in terms of simple completion rates for the experimental conditions.

Results and discussion. Participants were required to complete the two simulations within a 1-hr experimental session. As noted, however, most participants found the population simulation quite challenging, and many (24 out of 63) failed to finish within the allotted time. Given that ability to complete the simulation is obviously a good indicator of how difficult each participant found the task, and because it is directly related to our dependent variable of solution time, these participants were included in the analyses. Each was conservatively given a score of 2,000 time steps for their unfinished attempts (slightly less than the longest time that any participant took to successfully complete the task, which was 2,174 steps). On average, participants spent approximately 30 min on the population task. Those who completed the task took an average of about 20 min to do so, whereas those who failed to finish worked on the task for an average of 45 min (stopping at the end of the 55-min session).

A 2 (goal consistency) × 2 (test type) factorial analysis of variance (ANOVA) revealed reliable differences between conditions. A main effect of test type, $F(1, 59) = 27.77$, $\eta^2 = .32$, $p < .001$, reflected the fact that participants took considerably longer to complete the population stabilizing task than the population maximizing task (averages of 1,453 [*SD* = 785] and 343 [*SD* = 642] time steps, respectively). More relevant to our current interests was the main effect of goal consistency, $F(1, 59) = 4.59$, $\eta^2 = .07$, $p = .036$. Participants required reliably fewer trials to complete the population task when it involved achieving a goal that was analogous to that of the training task and thus involved an analogous solution strategy (681 [*SD* = 825] and 1,104 [*SD* = 943] steps for consistent and inconsistent problems, respectively). There were no reliable interaction effects. Given that so many participants failed to complete the transfer task, it also makes sense to analyze the results in terms of simple completion rates. Overall, significantly more participants were able to finish the population task when its goal was consistent with the prior task than when it was inconsistent (75% vs. 48%, respectively), $\chi^2(1, N = 63) = 4.73$, $p = .029$.

The data indicate analogical transfer between the two tasks. Participants were significantly more successful on the population task when its goal and optimal strategy were analogous to those from the ball simulation. This advantage contrasts with most research on analogical transfer, given the great dissimilarities between the two tasks in terms of their content domain, their perceptual appearance, their level of abstraction (moving visual entities vs. text display), and time course (real-time interaction vs. discrete time steps).

We suggest that the perceptually grounded training task is providing participants with a concrete model for structuring the subsequent transfer task. As reflected by participants' performance, the population task is quite challenging. Although the actual situation *described* by the task is of course concrete, the simulation itself is abstracted in a number of ways, and the relationships between the variables are difficult to immediately conceptualize. The visually concrete oscillating ball system, which makes the relevant relationships both explicit and salient, could provide the basis for a mental representation that would allow participants to organize and understand this less intuitive system.

This result dovetails nicely with some previous research by Bassok and colleagues (Alibali, Bassok, Solomon, Syc, & Goldin-Meadow, 1999; Bassok & Olseth, 1995). In studying the relative transfer between systems in which change was continuous versus discrete, those researchers hypothesized—and found—that the dynamics of large populations were construed as examples of continuous change. This is consistent with our view that the ball task in our study, which exhibits continuous motion and change, provides a good basis for people's mental models of the population task, despite the latter task's discrete values, time steps, and user interactions.

We assert that the concreteness of the training task—and specifically its spatial, dynamic instantiation—is critical in supporting this kind of transfer. If this suggestion is correct, it should also suggest some boundary conditions for the observed effects. For instance, such transfer should not be observed unless the training task is presented in a way that makes both the components and the relationships within the system concretely salient. Furthermore, the mental representations involved must be structurally compatible and easy to map to one another conceptually. Experiments 1b and 1c examine these issues.

Experiment 1b

The results of Experiment 1a are consistent with seemingly "far" transfer occurring when a training case can provide a mental model that can be used by the transfer case. This interpretation relies on the fact that the initial task is a concrete, spatial instantiation of the relevant principle. Of course, it is possible that something about this particular resonance structure makes it especially conducive to learning and transfer and that the concreteness of the particular instantiations was irrelevant in this case.

One straightforward test of this possibility would be simply to reverse the order of the tasks. If the training on the population task—which is not overtly spatial or perceptual—is found to support transfer to the ball system, then this would provide evidence against our claims. The current study explores this possibility. Of course, it is important to note that even disregarding the issue of concreteness, there is no guarantee that transfer between two domains will be symmetric. In fact, there are examples in the literature in which this is explicitly not the case, with transfer being substantially greater in one direction than the other (see e.g., Bassok & Holyoak, 1989; Bassok & Olseth, 1995). However, given that evidence for transfer from the population task would undermine our general claims, this experiment represents an important control.

Method.

Participants. Fifty-six Indiana University undergraduates participated in the study for partial course credit.

Materials and design. The tasks and design were identical to those in Experiment 1a, but the order of the simulations was reversed. Each participant began with one of the two versions of the population task (stabilize or maximize), followed by one of the two versions of the ball simulation. Individuals who had not completed the training (population) task within 45 min were stopped and told to proceed to the transfer (ball) task. The dependent measure in this study is the time required to complete the ball task, averaged across the seven trials.

Results and discussion. A 2 (goal consistency) × 2 (test type) factorial ANOVA did not indicate any effects of analogous goals. Although we observed that the maximize condition had faster average completion times than did the stabilize condition (32 s [*SD* = 26.5] vs. 51 s [*SD* = 38.3], respectively), $F(1, 52) = 5.02$, $\eta^2 = .09$, $p = .029$, as in the population task, there was no main effect of goal consistency, $F(1, 52) = 0.01$, $\eta^2 = .00$, $p = .913$. Participants in this study, in contrast to in the first experiment, were no faster in completing the transfer task when its goal was analogous to that of the training task. There were no reliable interaction effects. (Completion rates and time steps for all experiments are given in Table 1.)

One complicating issue is that, as in Experiment 1a, many participants (25 of 59) failed to complete the population task within the allotted time. Because this population task was the training task in the current study, an absence of transfer could simply reflect a poor (or nonexistent) representation of the relevant principle. We therefore performed the same 2 × 2 analysis on only those participants who had successfully completed the population task. Again, there was no indication of a difference between goal consistency conditions, $F(1, 27) = 0.26$, $\eta^2 = .01$, $p = .612$.

Together with the results from Experiment 1a, these findings are consistent with a kind of transfer that relies on the concrete, spatial aspects of the training case. Transfer is observed when the initial system may straightforwardly serve as a concrete mental model for the subsequent task. When the relevant variables in the first task are not overtly and saliently spatial, as in the current study, no such transfer occurs.

Table 1
Completion Time Steps (and Completion Rates) Across All Studies

Condition	1a	1b	1c	2	3	4	5
Consistent goal							
Time steps	681	40.2	840	483	1,045	644	692
Rate (%)	75		64	79	55	73	73
Inconsistent goal							
Time steps	1,104	38.9	993	957	1,032	1,099	984
Rate (%)	48		55	57	55	53	60
Control							
Time steps				1,020	1,004		
Rate (%)				58	58		

Experiment 1c

Certain characteristics are valuable in a representation that is to serve as a mental model. For instance, given that the role of such models is to simplify the understanding of complex external situations, a represented model should itself be easy to process, with clearly defined parts and relationships, and should be flexible enough to provide good inferential power. Furthermore, because the inferences that are made must ultimately be mapped back to the external situation itself, the relevant interpretations of the parts and relationships should be consistent between the model and the real-world case. Because these interpretations of each system are so important in achieving an appropriate and effective mapping, it is possible that seemingly minor changes in the structure of a case may have a profound effect on transfer between situations. In the current study, we made one such change: The direction of the ball system was reversed, with the fan placed on the right-hand side, blowing leftward, and the maximization goal being on the far left of the system.

Our reasoning is as follows: The population task has distinct, meaningful directions; the population is explicitly either increasing or decreasing, and the use of media applies a force in the increasing direction. At first glance, the ball system seems to lack such inherent directionality. Leftward and rightward motion appear fundamentally equivalent and interchangeable. However, there are reasons to think that this is not the case, especially in the system's role as a model for the population task. There is considerable evidence that individuals (at least those from Western societies) construe the leftward direction as "decreasing" and the rightward as "increasing." For instance, Dehaene, Bossini, and Giraux (1993) found that participants were faster to respond to lower numerical values with their left hands and faster to respond to higher values with their right hands. This basic pattern, known as the SNARC effect, has been replicated in dozens of studies (see Wood, Nuerk, Willmes, & Fischer, 2008, for a recent meta-analysis of over 100 studies). A related finding comes from more recent work involving patients with unilateral neglect, a deficit in the perception and representation of stimuli in the left visual field (including mental images). Such patients were found to have systematic impairments in their numerical judgments, in a pattern consistent with a similar neglect of the lower end of a canonical number line (Zorzi, Priftis, & Umilta, 2002).

In terms of this mapping between direction and magnitude, the ball system from Experiment 1a provides an apt model for the population task. In both cases, the user interaction (fan or media) adds a force in the "increasing" direction. The maximization task for the ball system, as for the population task, involves achieving a particularly "high" (i.e., rightmost) value, and this goal is accomplished by applying force when the value is already "increasing" (moving rightward). The stabilization goal in both tasks involves applying a force when values are "decreasing." Thus, the conceptual mapping between these systems supports the transfer of appropriate strategies. If participants have a natural tendency to translate population increases to rightward movements in space, then a congruent ball training scenario would lead to the development of a spatial model that could be applied to both tasks.

If participants use the ball system as the basis of a mental model for the population task, then reversing its direction should eliminate (or even reverse) this conceptual compatibility. Strategies that involve increasing (i.e., rightward) magnitudes in the training task would now involve decreasing magnitudes at transfer and vice versa. Thus, we predict that transfer will not be observed under these conditions. However, if participants rely on more abstract representations that do not rely on concrete spatial models, such a minor alteration of the simulation should make little if any difference in transfer.

Method.

Participants. Fifty-six Indiana University undergraduates participated in the study for partial course credit.

Materials and design. The experimental design and tasks were identical to those in the previous study, with one small modification. In the current study, the fan in the ball task was located to the right of the oscillating ball system, blowing leftward. Because of this change, the maximizing ball condition now required the participant to move the ball to the extreme left of the system rather than the extreme right (see Figure 3).

Results and discussion. A 2 (goal consistency) × 2 (test type) factorial ANOVA showed no difference between the goal consistency conditions, $F(1, 52) = 0.39$, $\eta^2 = .01$, $p = .533$. As predicted, participants in this study were no faster in completing the transfer task when its goal was analogous to that of the training task. As in previous studies, test type was a highly reliable predictor of performance, $F(1, 52) = 116.02$, $\eta^2 = .69$, $p < .001$, with participants completing the maximize goal much more quickly and successfully than the stabilize goal (averages of 1,730 [*SD* = 647] and 227 [*SD* = 346] time steps, respectively). There were no reliable interaction effects.

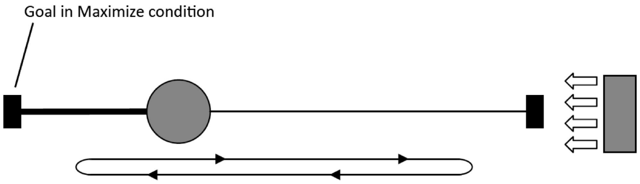


Figure 3. Schematic of the training task in Experiment 1c.

The fact that reversing the direction of the ball system eliminated transfer suggests that participants were relying on a model that is concretely similar to the ball system. Rather than simply transferring propositional representations of principles such as combining and opposing forces, individuals seem to have been using a more specifically instantiated perceptual representation that retains seemingly irrelevant information, such as left–right direction. When this information is incompatible with participants' conceptual understanding of the transfer system, mapping and transfer is impeded.

One possible alternative explanation for these results is that participants in the current study simply learned the relevant principle less well. Indeed, the average time steps necessary for completion of the ball task were higher in this study than in Experiment 1a (these experiments recorded time steps rather than simple completion times; 1,186 [*SD* = 1,351] vs. 790 [*SD* = 690] for Experiments 1c and 1a, respectively), $t(188) = 2.05$, $\eta^2 = .04$, $p = .043$. However, each participant completed the ball task seven times, so a better metric of learning would be performance at the *end* of the task. A comparison of completion times for each participant's final trial showed no differences between experiments (456 s [*SD* = 459] vs. 391 s [*SD* = 436] for Experiments 1c and 1a, respectively), $t(188) = 0.80$, $\eta^2 = .00$, $p = .428$, suggesting that learning did not differ for the two groups.

Interestingly, by showing that effects in these studies are not simply relying on more abstracted principles, such as "combining forces" or "opposing forces," this experiment also demonstrates the potential fragility of this sort of transfer. There is probably a trade-off between the flexibility of those more principle-based approaches and the cognitive ease of generating inferences with a spatial, analog model.

Experiment 2

Experiment 1a is consistent with our claim that analogical transfer may occur between overtly dissimilar cases if the mental representations of those cases share concrete similarities. In particular, we suggest that participants in our first study used the perceptual, spatial features and relationships presented in the oscillating ball simulation as the basis for constructing a concretely similar model of the population task. The results of our study run counter to the great majority of existing findings on analogical transfer. As such, one goal of Experiment 2 is simply to replicate our results. The more theoretically relevant goal is to further examine the nature of the representations underlying these effects.

One possible characteristic of these representations is implicit in the design of the study itself. Our experiments measure the degree to which participants transfer a particular solution strategy—a specific method of interacting with a system—from one situation to another. However, it might have been reasonable instead to predict that participants would map their knowledge of the entire set of rules governing the system, not just a particular manipulation strategy, because the two systems were completely isomorphic. In other words, whether a participant's goal is stabilization or maximization, the underlying dynamics of opposing forces and intrinsic oscillations were preserved. On its own, this could have led to positive transfer in all conditions and thus little or no difference between the groups. In contrast, we have been working under the assumption that participants' representations of the ball task are formed with respect to their particular perspective within the system and that the strategies that are transferred are represented in relation to this perspective. However, this remains an empirical question.

The current experiment introduces a control condition to evaluate this issue. Specifically, although Experiment 1a provides evidence for goal-based transfer, it does not rule out the possibility of additional system-based transfer, which would facilitate performance regardless of goal consistency. If it is exclusively a procedural strategy from a particular perspective that is being transferred, then the control group performance should be roughly equivalent to the inconsistent-goal condition. If, on the other hand, participants are benefiting from their exposure to the analogous structure in general, then those in the control condition should perform more poorly than those in both of the experimental conditions.

The current experiment also assesses participants' perceptions of the similarity between the two tasks, particularly in their structural commonalities. Most analogy researchers assume, on the basis of both empirical and theoretical considerations, that the explicit mapping of correspondences between cases is an essential step in analogical transfer (see e.g., Falkenhainer, Forbus, & Gentner, 1989; Hummel & Holyoak, 1997; Keane, Ledgeway, & Duff, 1994; though see Ripoll, Brude, & Coulon, 2003). If so, participants' recognition of the structural commonalities between the ball and population simulations should be a strong predictor of transfer.

Method.

Participants. Ninety-one Indiana University undergraduates participated in this study for partial course credit.

Materials and design. The overall structure of this experiment was similar to that of Experiment 1, with a few important differences. First, we included a control condition to explore the possibility that exposure to an analogous system was benefiting all participants, regardless of the consistency of the goals between the two tasks. The control task required participants to guide a spacecraft to its home planet through the appropriate placement of an "attractor" in space. The attractor exerted an attractive force on the spacecraft that was inversely proportional to the distance between them; thus, as the craft moved closer to the attractor, its acceleration toward the attractor increased. The spacecraft in question would otherwise follow a set trajectory—participants had no method of moving the craft other than by the placement of the attractor. The task therefore required participants to find the particular placement of the attractor that would cause the ship's trajectory to curve until it reached the destination planet. Thus, the control task contained the fundamental mechanical elements of the experimental conditions—motion along a constant vector that is altered by accelerating forces from a stationary point—but the overall relational structure of the system was quite different. The experiment therefore had a 3 (task consistency: same structure and consistent goal, same structure and inconsistent goal, different structure [control]) × 2 (population task type: stabilize or maximize) factorial design.

We also took steps to simplify the population task somewhat. As reported, a significant number of participants in the first experiment failed to complete the task within the 1-hr session. Although this is interesting from a theoretical perspective and provides useful data about the relative difficulty of the task for the different experimental groups, it also introduces a fixed ceiling for solution times and may therefore be obscuring some interesting variance in the data. We therefore added a simple visual display—a line graph, with population on the y-axis and time steps on the x-axis—to both versions of the population task in order to facilitate the tracking of population changes over time.

After the population task, two measures were employed to determine participants' explicit understanding of the relationship between the tasks. (These tasks were not administered to the control group, because their tasks were not analogous). First, we asked a series of open-ended questions to assess awareness that there was any relationship between the ball and population tasks. Participants were first asked for their general response to the tasks and whether they had noticed anything interesting or unusual about them. Next, they were asked (through open-ended questions) how similar they found the two tasks and to describe any similarities they had noticed. Finally, if participants reported that they had found the tasks similar, they were asked to report the point in the session at which they had first noticed this similarity. Next, participants completed a matching task, in which they selected which component from the population task corresponded to a particular component from the ball task. For example, the fan corresponded to media investment. The ball task components were presented one at a time to minimize responses on the basis of a process of elimination across the entire set. The following six correspondences were matched in total:

- Location of ball: population
- Direction and speed of the ball: appeal
- How much the ball is speeding up or slowing down: change in appeal
- Right elastic band: force that makes the city more attractive when the population is low
- Left elastic band: force that makes the city less attractive when the population is high
- Fan: media investment

Results and discussion.

Despite attempts to simplify the population task, many participants (29 out of 91, or 28%) still failed to finish within the allotted time. As in the previous experiments, these participants were given solution times of 2,000 time steps.

A 3 (goal consistency) × 2 (test type) factorial ANOVA revealed reliable differences between conditions. A main effect of test type, $F(1, 85) = 36.17$, $\eta^2 = .28$, $p < .001$, again reflected the fact that participants took reliably longer to complete the population stabilization task than the population maximizing task. More important, we again found a main effect of the relationship between the two tasks' goals, $F(2, 85) = 3.59$, $\eta^2 = .08$, $p = .032$. There were no reliable interaction effects. Post hoc analyses using Tukey's honestly significant difference procedure revealed reliable differences between the consistent- and inconsistent-goal groups (484 [$SD = 752$] vs. 957 [$SD = 939$] time steps, respectively; $p = .042$) and between the consistent-goal and the control groups (484 [$SD = 752$] vs. 1,020 [$SD = 883$] time steps, respectively; $p = .018$) but found no difference between the control and the inconsistent-goal conditions ($p = .939$). A similar pattern emerges from analysis of completion rates: 79% of participants in the consistent-goal group successfully completed the population task, compared with 57% and 58% in the inconsistent-goal and control groups, respectively. The difference between the consistent and inconsistent groups' completion rates is significant, $\chi^2(1, N = 58) = 4.27, p = .039$.

Experiment 2 therefore replicates the basic finding of Experiment 1a, with participants completing the transfer task significantly faster if it required a strategy that was analogous to that of the training task. Additionally, this experiment found no facilitation for simply interacting with and learning the rules of a system with the same structure, given that the inconsistent-goal group performed no better than did the control condition. Rather, the transfer seemed to involve strategies for interacting with the system, from a particular goal-based perspective.

Next, we analyzed participants' responses to the open-ended questions and the correspondence-matching task. Open-ended responses were coded and assessed for whether participants reported noticing any relevant structural commonalities during the course of the tasks. Similarities that were not relevant to the analogous structure were not counted (e.g., "Both involved clicking the mouse button"), nor were similarities that participants reported noticing after completion of the population task. Finally, the correspondence-matching tasks produced scores between 0 and 6, reflecting the number of correct matches.

Despite the added visual display, which made the oscillating movement of the population quite salient, only about one third of the participants in the experimental groups (17 out of 58) reported noticing any structural commonalities between the tasks. This is consistent with prior findings of poor explicit reminding between superficially dissimilar but analogous situations, even when they are in close temporal proximity. Not surprisingly, those participants who noticed that the two tasks were analogous performed better overall on the transfer task than did those who did not (304 [*SD* = 482] vs. 917 [*SD* = 951], respectively), $t(57) = 2.52, \eta^2 = .10, p = .015$. However, when looking separately at those who did versus did not recognize the analogy, we found similar numerical advantages for consistent- over inconsistent-goal conditions, though neither recognition group was statistically reliable on its own: 164 (*SD* = 223) versus 562 (*SD* = 721) time steps, respectively, $t(16) = 1.73, \eta^2 = .17, p = .104$, for those who recognized some commonalities between tasks, and 704 (*SD* = 906) versus 1,048 (*SD* = 972) time steps, respectively, $t(40) = 1.14, \eta^2 = .03, p = .26$, for those who did not (see Figure 4; there was no interaction between condition and recognition of commonalities). This indicates that reported awareness of the relationship between the tasks, although generally beneficial for performance, was not a necessary condition for transfer.

A similar conclusion may be drawn from the results of the correspondence-matching task. Overall, performance on this task was poor (averaging 27% correct). More interestingly, there was no correlation between accuracy in identifying explicitly probed correspondences and performance on the transfer task for either condition (in contrast to the general benefit associated with recognition in the open-ended questions discussed earlier). In fact, transfer was not found to be related to any particular correspondence item: Accuracy on even the seemingly most fundamental correspondences was uncorrelated with transfer performance (by point-biserial analysis), including the mappings between fan and media investment and between ball location and population. Knowledge of correspondences was evidently not related to transfer between tasks.

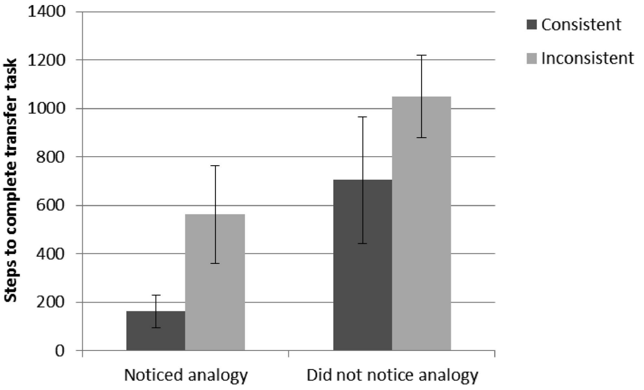


Figure 4. Performance on the transfer task by participants who noticed and did not notice the analogy between tasks in Experiment 2. Error bars indicate standard errors.

One counterintuitive aspect of our results is the fact that although explicit recognition of the analogy did not seem beneficial in terms of transfer (measured as differences between congruent and noncongruent conditions), it was beneficial in general, being associated with better overall performance. At first glance, these two results may seem hard to reconcile. However, it is likely that recognition of the analogy is not beneficial in itself but rather that those individuals who are likely to notice the analogy (because of attentiveness, intelligence, etc.) are also more likely to be successful on the transfer task. (From a methodological perspective, one incidental benefit of the advantage for those who recognize the analogy is that it serves as a sort of check on the measure itself. That is, the fact that our measure of recognition is associated with reliable differences between participants suggests that it is indeed capturing some relevant information.)

One obvious way that our overall pattern of results could be interpreted is in terms of the considerable literature on implicit learning and memory. Our results suggest that transfer is occurring even in the absence of reported awareness of the structural relationship between the cases. Although such awareness appeared to be beneficial to overall performance (those who recognized the analogy required many fewer trials to complete the transfer task), similar patterns of transfer were observed in those who did not report noticing the analogy. An interpretation in terms of implicit processing would suggest that participants are acquiring and applying structured representations in a way that is somehow dissociated from explicit declarative knowledge.

Such an interpretation would be consistent with a few previous studies suggesting implicit transfer between analogous cases. For instance, Brooks and Vokey (1991; Vokey & Brooks, 1992) presented evidence suggesting that knowledge applied during artificial grammar learning is in the form of analogies to specific prior items. Similarly, Greene and colleagues (Greene, Spellman, Dusek, Eichenbaum, & Levy, 2001; Gross & Greene, 2007) have reported that the global structural relationships within a set of items (e.g., transitive or transverse relationships) may be transferred to a new set without participants' awareness. Other research has found evidence that prior exposure to analogs may prime specific problem-solving strategies (Schunn & Dunbar, 1996) and influence text interpretation (Day & Gentner, 2007), even when participants deny being aware of this influence.

However, this interpretation conflicts with the bulk of previous research, which suggests a strong explicit component in analogical transfer. For instance, although spontaneous transfer is often quite rare, it becomes commonplace after an explicit connection is made between analogous cases (see e.g., Gick & Holyoak, 1980, 1983). Moreover, more recent research has increasingly called into question the very idea of implicit memory, at least as it has generally been considered (see Shanks, 2005, for a review). Some researchers have argued that most types of apparently implicit effects result from measurements of participants' explicit knowledge that are either incomplete (largely due to problems with subjective reports) or inappropriate (ignoring the knowledge that is actually used in a task and instead asking questions that follow the researchers' assumptions). For instance, classic findings on the implicit learning of artificial grammars (Reber, 1967) have more recently been explained in terms of the explicit learning of specific subsets of consecutive characters (see e.g., Perruchet & Pacteau, 1990). Such explicit knowledge was overlooked in the original studies, however, because participants were asked only about their awareness of more abstract grammatical rules.

Although the open-ended nature of our posttest questions suggests that we weren't asking participants about irrelevant aspects of their knowledge, it also leaves open the possibility that relevant knowledge might have been left untapped. However, regardless of whether the results of our study reflect implicit processes in the most traditional sense, the fact that participants show transfer that is independent of their explicit reports (measured similarly to in previous studies) differentiates these findings from the great majority of studies on analogical processing and is worth further examination.

In fact, our preferred interpretation of these phenomena is consistent with the more recent reinterpretation of implicit effects. We would argue that participants *are* acquiring and using information that is different from what is being assessed in our posttest questions (the *information criterion*; Shanks & St. John, 1994). What is surprising is that these tests seem to capture what many theorists would assume are the fundamental bases for analogical transfer: explicit correspondences between the two systems.

Experiment 3

The dissociation between transfer and reported understanding of the analogy between the systems is surprising, given that most theories of analogy argue that the mapping of correspondences between cases is an essential step in analogical transfer (see e.g., Falkenhainer et al., 1989; Hummel & Holyoak, 1997; Keane et al., 1994; though see Ripoll et al., 2003). However, this finding is essentially correlational, leaving the exact relationship between transfer and explicit knowledge unclear. For example, recognition of the analogy and faster completion of the task could each be the independent result of individual differences in areas such as intelligence or engagement in the experiment. This would help to explain the fact that although participants who recognized the analogy were faster overall, the difference between goal-consistency conditions was the same regardless of recognition. A related possibility is that a more rapid understanding of the system underlying the population task may itself cause explicit recognition to occur.

Experiments 3 and 4 explore these issues more closely by directly informing participants about the relationship between the tasks. In the current experiment, participants are explicitly told that the population task is analogous to the ball system and are taught the correspondences between the two systems before attempting to complete the transfer task. Although these experiments are largely exploratory in nature, some reasonable sets of competing predictions may be made. For example, if explicit knowledge of the analogy is itself a cause of facilitated performance, then we might expect all participants in the analogy conditions to show facilitation. In this case, both consistent- and inconsistent-goal conditions would perform better than the control condition, with a likely additional benefit for goal consistency. If, on the other hand, both performance and recognition are being driven by some separate factor, or superior performance is itself somehow causing recognition, then the pattern of results should be more similar to the overall pattern seen in Experiment 2, with inconsistent-goal and control conditions being comparable and both being inferior to the consistent-goal condition. Another possibility is that explicit knowledge of the analogy may actually impair performance for some individuals by promoting reliance on a deliberate, rule-based strategy, to the detriment of the relevant implicit procedural knowledge (see e.g., Reber, 1976; also, perhaps related to verbal overshadowing phenomena, see Schooler & Engstler-Schooler, 1990). In this case, performance may become worse overall relative to the prior experiments.

Method.

Participants. Sixty-one Indiana University undergraduates participated in this study for partial course credit.

Materials and design. As in Experiment 2, participants began by completing either the control task or one of the two versions of the ball simulations. Next, they were briefly exposed to the population simulation. Participants first read the general description and instructions for that simulation but were not given any specific goal to achieve. Instead, they were instructed to interact freely with the system and to observe how their decisions to use or not use media affected the population over time. This interaction lasted 3 min, with an on-screen timer indicating the time remaining.

Next, the participants in the two analogy conditions were informed of the structural relationship between the two systems. They were told that

> although the two tasks involve very different situations, they are actually alike in some more abstract ways. That is, the way that the individual parts relate to each other is similar in both tasks, and the two systems operate under similar rules.

They then completed the correspondence-matching task described in Experiment 2, indicating which components of the two simulations corresponded with each other. Unlike in the previous study, however, participants repeated this task until they reached 100% accuracy. After each block of six correspondence questions, they were given simple numerical feedback on their performance (e.g., "3 out of 6 correct") and told to try again until a perfect score was achieved. Because there was no structural relationship between the control and population tasks, participants in the control condition answered a series of multiple-choice questions about the population task during this phase, a procedure that they similarly repeated until a 100% criterion was met. All participants were able to view the verbal description of the population system at any time during this phase of the experiment by clicking a button on the main screen. Finally, all participants completed the population task with one of the two standard goals, either stabilizing or maximizing the population. (Given that the graph of the population over time from Experiment 2 did not appear to have a significant effect on performance, it was not included in this or subsequent studies).

Results and discussion. Completion rates were somewhat lower than in the first two studies, with only 56% of participants completing the population task within the experimental session. This reflects a sharp decline in performance by those in the consistent-goal condition (55%, compared with 84% in Experiment 2), whereas completion rates for those in the inconsistent and control conditions were similar to those in the previous studies. Thus, the decline does not appear to simply reflect the reduction in the available time resulting from the additional training task. Analysis of the noncompleting participants was performed as in previous experiments.

Unlike in Experiments 1a and 2, a 3 (goal consistency) × 2 (test type) factorial ANOVA revealed no effects of goal consistency. Although the population maximizing task was again completed more quickly than the population stabilization task (764 [*SD* = 830] vs. 1,282 [*SD* = 1,282] time steps, respectively), $F(1, 55) = 5.17$, $\eta^2 = .69$, $p = .027$, goal consistency appeared to have no effect on completion times (1,032 steps for consistent, 1,045 for inconsistent, 1,004 for control), $F(2, 55) < .02$, $\eta^2 = .00$, $p = .981$. This is also reflected in the completion rates for the three goal conditions: 55%, 55%, and 58%, for consistent, inconsistent, and control, respectively, $\chi^2(2, N = 61) = 0.05$, $p = .973$. There were no reliable interaction effects.

There was considerable variation in the number of blocks necessary to reach the 100% criterion in the correspondence-matching task, and overall the number was surprisingly high, with a median of nine blocks (excluding an outlier, who required 101 blocks, >5 *SD* from the mean). Only one participant was perfectly accurate on the first attempt. There was a small but reliable positive relationship between this measure and the time steps required to complete the population task ($r = .32$, $p < .05$).

Unlike in Experiments 1a and 2, there was no benefit for the participants who had prior experience with an analogous goal: Their completion rates and completion times were indistinguishable from those in the inconsistent and control conditions. This result appeared to be entirely due to a decrease in performance by the consistent-goal group, with data for the other two conditions being very similar to data in the previous studies. Thus, explicitly drawing attention to the relationship between the tasks not only failed to facilitate transfer but appeared to eliminate transfer altogether.

This finding is initially quite surprising. As discussed earlier, most researchers have concluded that the lack of memory access to an appropriate base example is the primary impediment to analogical reasoning. Consistent with this, research has found that explicit reminding of a relevant prior case can lead to robust transfer, even in situations where transfer is otherwise quite poor (see e.g., Gick & Holyoak, 1980, 1983). It would therefore have been reasonable to predict similar facilitation in the current study.

However, our results might be explained in terms of some of the existing literature on the relationship between explicit knowledge and implicit processes. For example, performance on artificial grammar learning tasks is impaired when participants are instructed to explicitly search for the relevant rules (see e.g., Brooks, 1975; Reber, 1976), suggesting that an explicit, analytic strategy may be interfering with the primarily implicit learning. Similar interference from explicit processing has been reported with tasks such as complex control systems (see e.g., Berry & Broadbent, 1988) and the learning of motoric procedural patterns (see e.g., Shea, Wulf, Whitacre, & Park, 2001). Researchers have suggested that the search for specific, verbalizable patterns in a complex task can result in reliance on incorrect rules (see e.g., Reber, 1976) rather than the more valid "guesses" associated with the application of implicit knowledge.

Alternatively, some researchers argue that explicit instructions may impair learning because they encourage an inappropriate allocation of attention (see e.g., Perruchet, Chambaron, & Ferrel-Chapus, 2003). For example, an active search for rules when learning exemplars from an artificial grammar may lead participants to focus on simple potential rules—such as classification based on the first or last letters of the string—to the detriment of learning the relevant substrings within the item. Although this kind of explanation does not map perfectly onto the current design (participants in our study are not informed of the analogy until encoding of the training task has finished), issues of attentional misallocation do seem potentially relevant. Specifically, by focusing on more abstract or decontextualized relationships between the tasks, participants may be overlooking the concrete perceptual information that is most relevant to the construction of an appropriate mental model.

This might help to account for some apparent tension between the results of the current experiment and those of our previous experiment. Experiment 2 found that those participants who reported noticing the analogy performed better overall and showed a pattern of transfer similar to that of those who did not notice the structural commonalities. In contrast, the present study, which made the relationship between the tasks explicit, found neither of these effects: Average performance was no better than in previous experiments (and was, in fact, numerically poorer), and there was no difference between conditions. These different patterns of results may be reconciled if one assumes that the knowledge of the analogy itself is not detrimental, but the intensive focus on explicit correspondences distracts participants from the perceptual and spatial information relevant for the formation of the mental model. Experiment 4 explores this possibility by making the analogy explicit through instruction but without the cognitively demanding training on specific correspondences.

Experiment 4

Method.

Participants. Sixty-five Indiana University undergraduates participated in the study for partial course credit.

Materials and design. The materials and design were the same as those of Experiment 2, but additional wording was included in the instructions for the population task, explicitly noting that the two tasks were analogous. Added to the beginning of the description that preceded the task were the following sentences:

> The following task is *analogous* to the one that you just completed. An analogy is a situation in which two things are structurally similar, even though they appear different on the surface. For instance, the

> atom may be considered analogous to the solar system, because they have a similar organization in spite of their many differences. Likewise, even though your tasks may not appear similar on the surface, the principles underlying their operation and the relationships between their parts are the same.

At the end of the instructions, immediately before the population task began, the following sentences were added: "Remember that this task is analogous to the ball task that you just completed. Its underlying behavior is the same as the previous task." Note that unlike in Experiment 3, there was no explicit training on the correspondences between the tasks (although, as in Experiment 2, a correspondences test was given at the end of the session).

Results and discussion. Completion rates were similar to those in Experiment 1a, with 24 of 65 failing to finish within the experimental session. These participants were analyzed as in the previous studies. A 2 (goal consistency) × 2 (test type) factorial ANOVA revealed reliable differences between conditions. The population stabilization task again took considerably longer to complete than did the maximizing task (1,399 [*SD* = 849] vs. 286 [*SD* = 483] time steps, respectively), $F(1, 61) = 43.63$, $\eta^2 = .42$, $p < .001$. More important, participants required reliably fewer trials to complete the population task when its goal was analogous to that of the training task (644 [*SD* = 809] vs. 1,099 [*SD* = 926] steps, respectively), $F(1, 61) = 4.59$, $\eta^2 = .07$, $p = .036$). There were no reliable interaction effects. Although a similar pattern was found in simple completion rates (.73 vs. .53 for goal-consistent and -inconsistent groups, respectively), this difference was not statistically reliable, $\chi^2(1, N = 65) = 2.68$, $p = .10$.

As described earlier, the instructions in this study were modified to explicitly draw participants' attention to the analogy between the tasks, in two separate instances. Despite these instructions, however, posttest responses indicated that most individuals failed to recognize this analogy: Only 25 of the 65 participants (38%) reported noticing any meaningful structural commonalities between the tasks. This rate was not appreciably higher than that of Experiment 2 (29%), in which no such instructions were included. As in that study, those participants who reported recognizing commonalities performed better overall on the transfer task than did those who didn't see the commonalities (434 [*SD* = 648] vs. 1,140 [*SD* = 921] time steps, respectively), $t(64) = 3.34$, $p = .001$. However, the numerical advantage of the consistent-goal over the inconsistent-goal group held regardless of whether commonalities were noticed (420 [*SD* = 601] vs. 442 [*SD* = 698] steps, respectively, for those who reported commonalities and 813 [*SD* = 874] vs. 1,407 [*SD* = 890] steps, respectively, for those who did not). This advantage was reliable for the latter group, $t(39) = 2.12$, $p = .041$, and there was no interaction between goal consistency and recognition of commonalities on performance.

Performance on the correspondences-matching task was somewhat higher in this experiment than in Experiment 2 (45% vs. 27%, respectively). However, as in that study, there was no reliable relationship to performance on the transfer task.

Combined with the findings from Experiments 2 and 3, the results of this study further suggest that the information that participants are acquiring and applying in these studies is different from the explicit mapping of correspondences that are widely assumed to underlie analogical transfer. Although explicit awareness of an analogy between tasks is not inherently detrimental to transfer, it does appear to be irrelevant, and under some circumstances it is distracting enough to impair performance. This is consistent with reliance on perceptual, spatial representations that can be translated fairly directly into a mental model of the transfer task, without the involvement of more abstract intermediate representations.

Experiment 5

The data thus far support the general claim that individuals may use a concrete situation as the basis of a mental model for a new case and therefore produce seemingly far transfer. However, many questions remain about the representations and processes underlying these effects. Experiment 5 begins to explore these issues, focusing on the role of interaction and intervention during learning.

The claim for the use of concrete, perceptual mental simulations naturally invites comparison to the growing literature on grounded and "embodied" approaches to cognition (see e.g., Barsalou, 2008). A standard corollary of this approach is the argument that cognition is "situated" within the external world, operating with respect to the constantly interacting flow of perceptual input and motoric output involved in goal-directed behavior (see e.g., Chiel & Beer, 1997; Clark, 1997). As such, it might be predicted that active motoric interaction would be beneficial for this kind of learning.

In the current experiment, we manipulated participants' level of active control over the training system by adding conditions in which the strategies in the ball task were passively observed. In addition to providing some insight about the representations involved in this kind of transfer, findings on the role of active intervention versus simple observational learning have relevance in a wide range of domains, including the active literature on causal learning (see e.g., Pearl, 2000; Waldmann, Cheng, Hagmayer, & Blaisdell, 2008).

Method.

Participants. One hundred four Indiana University undergraduates participated in this study for partial course credit.

Materials and design. Although the rules and visual display for the ball system were the same as in previous studies, the ways in which participants interacted with the system were different. Rather than having the opportunity to interact freely with the simulation in order to achieve a specific goal, participants in the current study were guided through the process in one of two ways: either by passively observing one of the goals being reached or by being directly instructed on the specific actions to take at each step. These are referred to as the observe and do conditions, respectively. The task was divided into four brief phases, designed to familiarize participants with the system and the effects of the fan.

Participants in the observe condition simply watched each of the four phases and were not able to interact in any way (other than starting each phase). Each phase was preceded by a screen with a brief description of what they were about to watch, and participants clicked a button to begin each simulation. After reading a brief description of the system, the observe participants first watched the simulation operate uninterrupted for 15 s. The purpose of this phase was to familiarize participants with the general operation and oscillating motion of the system, and there was no activity from the fan. Next, they were instructed to observe what effects, if any, constant activation of the fan had on the system's operation. This second phase was designed to demonstrate the fact that constant application of force from the fan had no significant impact on the ball's motion. Participants observed the ball's motion without any force from the fan for approximately 3 s, at which time the fan was activated and remained active for the rest of the phase (15 s total). As discussed earlier, because the force from the fan increases the ball's amplitude as it travels away from the fan's location and decreases the amplitude as it moves back toward the fan, the net impact on the ball's motion in this case is negligible. Next, participants were instructed that they would "see what happens when the fan is used in a more specific way." For those in the stabilize condition, the instructions continued, "In this simulation, the fan will be active ONLY WHEN THE BALL IS MOVING LEFTWARD (toward the fan), and NOT when the ball is moving toward the right." For participants in the maximize condition, the directions were reversed. This simulation again began with approximately 3 s of the ball's independent motion, followed by action from the fan as described in the instructions. As in the previous studies, these actions caused the ball to either stabilize in the middle or to reach the extreme right side of the system. Finally, participants watched the third simulation again (preceded again by a specific description of the fan's activity).

The ball simulation followed the same general pattern for participants in the do condition, and the first phase (which involved simply watching the system without intervention) was identical to the description just given. For the remaining phases, however, participants in this condition were able to interact with the system, and they controlled all of the activity of the fan themselves (according to specific instructions). In the second phase, they were instructed to observe the effects of activating the fan constantly for several seconds. In the third and fourth phases, participants were given specific instructions regarding when to activate the fan, which would result in either the stabilization or the maximizing of the system (although these end goals were never explicitly stated). For example, participants in the stabilize condition were told, "Next, see what happens when you use the fan in a more specific way. Try activating the fan ONLY WHEN THE BALL IS MOVING LEFTWARD (toward the fan), and NOT when the ball is moving to the right." Thus, the visual display was approximately identical for those in the observe and do conditions. However, those in the do group were directly responsible for the activation of the fan, whereas the observe participants simply watched the simulation passively. Neither group acted in order to achieve any goal with respect to the ball's motion.

All participants were asked a series of brief questions after the ball simulation, primarily to support the perception that it represented an independent experiment (i.e., distinct from the subsequent population task). The following questions were asked: (1) "How realistic did you find the behavior of the simulated system?"; (2) "How intuitive was the system's behavior? Would you have been able to guess how it would respond to the fan?"; (3) "Have you ever interacted with a similar system in the real world? If so, please describe it." All participants then completed one of the two versions of the population task, as in the previous studies. Afterward, all participants were asked to describe the strategy that they had used (or attempted) in order to achieve the required goal. Finally, each answered questions about recognizing the similarities between the ball and population tasks and completed the correspondence-matching task, as in Experiment 2.

Results and discussion. Overall, completion rates were similar to those in previous experiments, with 35% of participants failing to finish the population task within the experimental session. As before, these participants were included in the analysis.

A 2 (goal consistency) × 2 (test type) × 2 (ball interaction type [observe vs. do]) ANOVA revealed reliable differences between groups. As expected, goal consistency had a reliable effect on completion time (692 [*SD* = 823] vs. 984 [*SD* = 865] time steps for consistent and inconsistent groups, respectively), $F(1, 96) = 4.13$, $\eta^2 = .04$, $p = .045$). Test type was also a significant factor, with the maximize goal again being completed much more quickly than the stabilize goal (397 [*SD* = 610] vs. 1,278 [*SD* = 837] steps, respectively), $F(1, 96) = 33.53$, $\eta^2 = .26$, $p < .001$. However, the method of interaction with the ball simulation appeared to have no impact on the transfer task, and the observe and do groups performed similarly (878 [*SD* = 846] vs. 798 [*SD* = 866] steps, respectively), $F(1, 96) = 0.34$, $\eta^2 = .00$, $p = .564$. There were no reliable interactions between any factors. Unlike in Experiments 1a and 2, analysis of the completion rates themselves did not reveal a reliable effect of goal consistency, $\chi^2(1, N = 104) = 2.11$, $p = .15$.

Experiment 5 thus provides an additional replication of the basic transfer result, with participants completing the population task more quickly when it was preceded by a task requiring an analogous strategy. This effect did not appear to depend on the degree of personal interaction required during the initial task, and both the observe and do groups showed superior performance when the two tasks had analogous goals.

In contrast with previous studies, there is some evidence for a relationship between performance on the transfer task and the correspondence-matching task in this experiment. Across all participants, there was a (nonsignificant) trend for better correspondence performance to be associated with somewhat shorter completion times. Closer inspection shows that this result reflects a relatively strong negative relationship between these measures for the consistent-goal group ($r = -.48$, $p < .001$) and no significant trends for the inconsistent-goal group ($r = -.08$, $p = .573$). This contrasts with the results from Experiments 2 and 3, in which there was no relationship between the measures for either group. One possible explanation for this disparity is the fact that the ball simulation in the current experiment presents the optimal strategy directly and succinctly, providing a better representation for explicit evaluation and comparison than in the previous studies, in which understanding of the base system could be more graded. However, given that this did not translate into better recognition of the analogy during the tasks themselves (as discussed later), it is possible that the correlations observed here reflect processing that occurred after the simulations, with the higher performing individuals also being more likely to recognize the correspondences once they are explicitly cued. Similarly, it could be the case that the causal direction is reversed: Strong performance on the transfer task reflects a better representation of that domain, which could support better explicit comparison. Further research will be required to interpret the relationship between these measures.

Consistent with previous findings, however, explicit recognition of the analogy between the tasks was quite low, with only 15 out of 104 participants (14%) reporting that they noticed any relevant structural commonalities during the experiment. In fact, this is about half the rate observed in Experiment 2, probably due to the absence of the salient graph used in that study. As in previous experiments, completion times were faster overall for the participants who did rather than did not recognize the commonalities (533 [*SD* = 659] vs. 892 [*SD* = 866] time steps, respectively), although in this case this difference was not statistically significant, $t(1, 103) = 1.53$, $\eta^2 = .02$, $p = .129$. The effects of analogical transfer were also not dependent upon awareness of the analogy. The observed facilitations (i.e., consistent-goal minus inconsistent-goal scores) for recognizers and nonrecognizers were quite similar (256 and 251 time steps, respectively). The overall pattern is therefore quite similar to those in Experiments 2 and 3: Recognition of the analogy is associated with faster overall completion, but these effects appear to be independent of the analogy manipulation.

A similar pattern emerges in the analysis of participants' reported strategies for solving the task. At the end of the transfer task, all participants were instructed: "Describe the strategy you used to complete the population task. Please be as specific as possible." These responses were coded for the presence of any strategy component that was consistent with the optimal strategy shown in the ball simulation. Some responses—such as "I was able to achieve 1 million very quickly by advertising when the population was increasing and not advertising when population was decreasing"—clearly reflected the correct strategy. However, credit was also given for strategies that only partially matched the ideal, such as using media for only a portion of the relevant phase of oscillation (e.g., "No media until it goes very high then comes back down then media at around 465000 and then no media till it comes back down to there and keep doing this until I was done").

Even by this fairly liberal criterion, only 27% of participants were coded as using a correct strategy. Many participants reported having no consistent strategy, and many others described strategies that relied on irrelevant information, such as the change in appeal value (e.g., acceleration) or whether the population was above or below a certain number. As would be expected, participants with the correct strategy completed the task more quickly overall than did those without such a strategy (345 [*SD* = 495] vs. 1,014 [*SD* = 877], respectively), $t(1, 103) = 3.76$, $\eta^2 = .12$, $p < .001$. However, as with the explicit recognition measure, this appeared to be completely independent of the analogical facilitation. Goal consistency produced similar levels of facilitation regardless of the accuracy of the strategy used (an advantage of 319 and 286 time steps, respectively, for those using correct vs. incorrect strategies).

The lack of any difference between the two ball interaction conditions (observe and do) seems to argue against a strong motor-driven explanation for the learning in these studies. Transfer and overall performance were roughly equivalent regardless of whether participants interacted with the system to produce the relevant outcome or simply watched passively as the simulation operated on its own. Motoric responses related to the stabilize or maximize goals were therefore apparently unnecessary for learning and transfer to take place.

General Discussion

The current set of experiments produced two notable findings. First, we found evidence for analogical transfer from a concrete, highly perceptual system to a very dissimilar domain and task. Participants in our studies were more successful in completing the population task when it was preceded by a concrete simulation that involved an analogous structure and strategy. As discussed, this result contrasts with the considerable existing evidence for poor or nonexistent transfer between superficially dissimilar cases. We argue that the transfer in these experiments occurs because participants are using the training simulation as the basis for a mental model that allows them to appropriately structure and make sense of the less intuitive transfer task. Thus, although the simulations themselves are not overtly similar, the translation of the population task into a concrete mental model means that transfer may be viewed as occurring between two concretely similar mental representations.

The second notable finding from these experiments was that participants' transfer was independent of their explicit reports. As in prior research, explicit recognition of the structural commonalities between tasks was quite infrequent. In our studies, however, the degree of analogy-based improvement on the transfer task was comparable for the participants who reported noticing the analogy and for those who did not. Moreover, transfer even appeared to be independent of participants' explicitly reported strategies for solving the task. Although participants who reported accurate strategies completed the task more quickly overall, the advantage from prior exposure to an analogous simulation was almost identical for those whose reported strategies were completely inappropriate. By these measures, participants appeared to be applying aspects of the appropriate strategy without recognizing that they were doing so.

This unexpected result warrants further examination. One straightforward interpretation is in terms of implicit learning and memory. As discussed earlier, the procedural nature of the relevant strategy makes this interpretation plausible. Many studies have reported that procedures (both motor and cognitive) may be acquired in a way that appears independent of participants' explicit awareness (see e.g., Berry & Broadbent, 1984; Cohen & Squire, 1980). Although these earlier studies found evidence for such learning only on repetitions of a single task—not between overtly dissimilar cases, as in our study—this is consistent with our general interpretation that these effects are occurring between concretely similar mental representations. As noted earlier, however, there has been skepticism among some researchers about previous interpretations of implicit learning and processes (see e.g., Shanks, 2005).

Another (not mutually exclusive) possibility is that the processes underlying the transfer in our experiments are somewhat different from those in most studies of analogy. Analogical transfer is generally thought to rely on an explicit mapping between cases, in which entities or concepts that play the same structural role in two representations are placed into correspondence with one another (see e.g., Falkenhainer et al., 1989; Hummel & Holyoak, 1997; Keane et al., 1994). In the current study, however, we suggest that participants may be using the ball system as the basis for a mental model of the population task. If so, there might not be a direct mapping between the ball and population tasks but rather something more like a priming of the relations involved (see e.g., Leech, Mareschal, & Cooper, 2008; Spellman, Holyoak, & Morrison, 2001). This could help to explain the fact that the strategies acquired appeared to be piecemeal (see e.g., Collins & Gentner, 1987; diSessa, 1982), represented from a particular perspective, rather than global and comprehensive (Experiment 2).

Both the concrete dissimilarities between the tasks and the dissociation between transfer and reported awareness differentiate the current studies from most of the existing analogy literature. Further research is required to fully understand the representations and processes that are involved in the effect observed here. However, there are some aspects of both the training and the transfer case that we believe are particularly relevant. Given the presumed role of mental models in these effects, one of the more important features is the spatial, dynamic nature of the learning task. Spatial representations are able to capture a great deal of information succinctly and to do so in a way that easily supports a variety of inferences. Perhaps more important, humans are inherently well equipped to process spatial information, making it an efficient and powerful representational format. Dynamic representations contain information about changes over time, which can capture the ways in which various forces may interact and the states that result from those interactions. In addition to the relevant findings already discussed (Catrambone et al., 2006; Pedone et al., 2001), some prior results from our lab are consistent with the benefits of dynamic spatial information in transfer. For example, training participants on an explicitly spatial simulation involving the principle of competitive specialization (in the context of ants foraging for food) produces positive transfer to tasks in which that principle is instantiated in a very different context (neural networks; Goldstone & Sakamoto, 2003; Goldstone & Son, 2005). Similarly, Hills, Todd, and Goldstone (2008, in press) found that exploration and exploitation strategies promoted by a task involving a literal search in physical space were carried over to a subsequent task involving the mental search for a word's anagrams. The dynamic, perceptual nature of our training task may also play a role in directing participants' attention, which is known to be an important factor in implicit or incidental pattern learning (see e.g., Jiménez & Méndez, 1999; Mayr, 1996; Nokes & Ash, 2010). This may even be operating at the level of influencing eye movements to highlight relevant features and relationships within the system (see e.g., Grant & Spivey, 2003).

The five experiments reported collectively sharpen our understanding of the nature of the constructed mental models that are responsible for the observed transfer. First, Experiments 1b and 1c, when compared with Experiment 1a, suggest that the models are spatial and perceptually based. Training on the population scenario does not improve performance on the ball scenario (Experiment 1b), and this is likely because the former's spatial nature is concealed and may be discovered only when it is preceded by the ball scenario. Experiment 1c suggests that mental models preserve relative spatial information such as the relations "left of" and "right of." Simply reversing the fan's blowing direction in the ball simulation prevents it from matching participants' model of the population simulation. Participants naturally translate quantities such as population into spatial representations, but their natural tendency is to map increasing quantity to rightward motion. Experiment 2 suggests that the participants' mental models are not established at the general level of a resonance system. If so, transfer between stabilize and maximize conditions would have been expected to surpass transfer from the control task. Instead, the participants' models appear to be connected closely to their specific goal in a scenario. Finally, the equivalent positive transfer found in the do and observe conditions of Experiment 5 suggests that the mental models that produce transfer do not include motoric representations. In sum, the experiments indicate ways in which the mental models are grounded in perceptual features, relative space, and participants' goals but are also capable of spanning superficially dissimilar scenarios with different motoric requirements.

In the transfer case, the analog representations and procedural strategies that we believe are underlying these effects would potentially be ill suited for the transfer of more discrete, propositional pieces of information, such as a specific formula or insight solution. Rather, the knowledge may be most likely to emerge in tasks that are themselves dynamic and that allow for flexible, complex patterns of interaction that unfold over time. When viewed from the perspective of traditional transfer studies, this might initially seem to severely restrict the scope of relevance for these sorts of effects. However, further consideration suggests that such tasks may in fact be extremely common in real-world contexts. In life, tasks are performed in real time, and similar types of problems arise repeatedly. Approaches to these problems develop incrementally and evolve with experience. Organizing and completing a project, negotiating social interactions with groups of people, mounting and defending an intellectual argument, learning a new domain or skill—all of these can involve managing complex dynamic systems of relationships between people, goals, environments, and time. In light of this, as well as the steady flow of findings suggesting that concrete mental representations play a role in everything from algebraic problem solving (see e.g., Landy & Goldstone, 2007) to interpersonal dynamics (see e.g., Briñol & Petty, 2008; Wolff, 2007), it seems reasonable to suggest that procedural, possibly implicit, mental representations may have an important influence across many aspects of human cognition.

References

Alibali, M. W., Bassok, M., Solomon, K. O., Syc, S. E., & Goldin-Meadow, S. (1999). Illuminating mental representations through speech and gesture. *Psychological Science, 10,* 327–333. doi:10.1111/1467-9280.00163

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59,* 617–645. doi:10.1146/annurev.psych.59.103006.093639

Bassok, M., & Holyoak, K. J. (1989). Interdomain transfer between isomorphic topics in algebra and physics. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 153–166. doi:10.1037/0278-7393.15.1.153

Bassok, M., & Olseth, K. L. (1995). Object-based representations: Transfer between cases of continuous and discrete models of change. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 1522–1538. doi:10.1037/0278-7393.21.6.1522

Berry, D. C., & Broadbent, D. E. (1984). On the relationship between task performance and associated verbalizable knowledge. *Quarterly Journal of Experimental Psychology, 36*A, 209–231.

Berry, D. C., & Broadbent, D. E. (1988). Interactive tasks and the implicit-explicit distinction. *British Journal of Psychology, 79,* 251–272.

Briñol, P., & Petty, R. E. (2008). Embodied persuasion: Fundamental processes by which bodily responses can impact attitudes. In G. R. Semin & E. R. Smith (Eds.), *Embodied grounding: Social, cognitive, affective, and neuroscientific approaches* (pp. 184–210). Cambridge, England: Cambridge University Press.

Brooks, L. R. (1975). Nonanalytic concept formation and memory for instances. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 169–211). New York, NY: Wiley.

Brooks, L. R., & Vokey, J. R. (1991). Abstract analogies and abstracted grammars: Comments on Reber (1989) and Mathews et al. (1989). *Journal of Experimental Psychology: General, 120,* 316–323. doi:10.1037/0096-3445.120.3.316

Catrambone, R., Craig, D. L., & Nersessian, N. J. (2006). The role of perceptually represented structure in analogical problem solving. *Memory & Cognition, 34,* 1126–1132.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5,* 121–152. doi:10.1207/s15516709cog0502_2

Chiel, H. J., & Beer, R. D. (1997). The brain has a body: Adaptive behavior emerges from interactions of nervous system, body and environment. *Trends in Neurosciences, 20,* 553–557. doi:10.1016/S0166-2236(97)01149-1

Clark, A. (1997). *Being there.* Cambridge, MA: MIT Press.

Clement, C., Mawby, R., & Giles, D. (1994). The effects of manifest relational similarity on analog retrieval. *Journal of Memory and Language, 33,* 396–420. doi:10.1006/jmla.1994.1019

Cohen, N. J., Poldrack, R. A., & Eichenbaum, H. (1997). Memory for items and memory for relations in the procedural/declarative memory framework. *Memory, 5,* 131–178. doi:10.1080/741941149

Cohen, N. J., & Squire, L. R. (1980, October 10). Preserved learning and retention of pattern analyzing skill in amnesia: Dissociation of knowing how and knowing that. *Science, 210,* 207–210. doi:10.1126/science.7414331

Collins, A., & Gentner, D. (1987). How people construct mental models. In D. Holland & N. Quinn (Eds.), *Cultural models in language and thought* (pp. 243–265). Cambridge, England: Cambridge University Press.

Day, S. B., & Gentner, D. (2007). Nonintentional analogical inference in text comprehension. *Memory & Cognition, 35,* 39–49.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and numerical magnitude. *Journal of Experimental Psychology: General, 122,* 371–396. doi:10.1037/0096-3445.122.3.371

Detterman, D. (1993). The case of prosecution: Transfer as an epiphenomenon. In D. K. Detterman & R. J. Sternberg (Eds.), *Transfer on trial: Intelligence, cognition, and instruction* (pp. 1–24). Norwood, NJ: Ablex.

diSessa, A. (1982). Unlearning Aristotelian physics: A study of knowledge-based learning. *Cognitive Science, 6,* 37–75. doi:10.1207/s15516709cog0601_2

Dunbar, K., & Blanchette, I. (2001). The in vivo/in vitro approach to cognition: The case of analogy. *Trends in Cognitive Sciences, 5,* 334–339. doi:10.1016/S1364-6613(00)01698-3

Falkenhainer, B., Forbus, K. D., & Gentner, D. (1989). The structure-mapping engine: Algorithm and examples. *Artificial Intelligence, 41,* 1–63. doi:10.1016/0004-3702(89)90077-5

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 7,* 155–170. doi:10.1207/s15516709cog0702_3

Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 99–129). Hillsdale, NJ: Erlbaum.

Gentner, D., Holyoak, K. J., & Kokinov, B. (Eds.). (2001). *The analogical mind: Perspectives from cognitive science.* Cambridge, MA: MIT Press.

Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95,* 393–408. doi:10.1037/0022-0663.95.2.393

Gentner, D., Ratterman, M. J., & Forbus, K. D. (1993). The roles of similarity in transfer: Separating retrievability from inferential soundness. *Cognitive Psychology, 25,* 524–575. doi:10.1006/cogp.1993.1013

Gentner, D., & Stevens, A. L. (Eds.). (1983). *Mental models.* Hillsdale, NJ: Erlbaum.

Gentner, D., & Toupin, C. (1986). Systematicity and surface similarity in the development of analogy. *Cognitive Science, 10,* 277–300. doi:10.1207/s15516709cog1003_2

Gibbs, R. (2006). *Embodiment and cognitive science.* New York, NY: Cambridge University Press.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology, 12,* 306–355. doi:10.1016/0010-0285(80)90013-4

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15,* 1–38. doi:10.1016/0010-0285(83)90002-6

Goldstone, R. L., & Sakamoto, Y. (2003). The transfer of abstract principles governing complex adaptive systems. *Cognitive Psychology, 46,* 414–466. doi:10.1016/S0010-0285(02)00519-4

Goldstone, R. L., & Son, J. Y. (2005). The transfer of scientific principles using concrete and idealized simulations. *Journal of the Learning Sciences, 14,* 69–110. doi:10.1207/s15327809jls1401_4

Grant, E. R., & Spivey, M. J. (2003). Eye movements and problem solving: Guiding attention guides thought. *Psychological Science, 14,* 462–466. doi:10.1111/1467-9280.02454

Greene, A. J., Spellman, B. A., Dusek, J. A., Eichenbaum, H. B., & Levy, W. B. (2001). Relational learning with and without awareness: Transitive inference using nonverbal stimuli in humans. *Memory & Cognition, 29,* 893–902.

Gross, W. L., & Greene, A. J. (2007). Analogical inference: The role of awareness in abstract learning. *Memory, 15,* 838–844. doi:10.1080/09658210701715469

Hayes, J. R., & Simon, H. A. (1977). Psychological differences among problem isomorphs. In N. J. Castellan, Jr., D. B. Pisone, & G. R. Potts (Eds.), *Cognitive theory* (pp. 21–41). Hillsdale, NJ: Erlbaum.

Hegarty, M. (1992). Mental animation: Inferring motion from static diagrams of mechanical systems. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 1084–1102. doi:10.1037/0278-7393.18.5.1084

Hegarty, M. (2004). Mechanical reasoning as mental simulation. *Trends in Cognitive Sciences, 8,* 280–285. doi:10.1016/j.tics.2004.04.001

Hesse, M. (1966). *Models and analogies in science.* Notre Dame, IN: University of Indiana Press.

Hills, T. T., Todd, P. M., & Goldstone, R. L. (2008). Search in external and internal spaces. *Psychological Science, 19,* 802–808. doi:10.1111/j.1467-9280.2008.02160.x

Hills, T. T., Todd, P. M., & Goldstone, R. L. (in press). Priming a central executive search process: Exploration and exploitation in generalized cognitive search processes. *Journal of Experimental Psychology: General.*

Hofstadter, D. R. (1996). *Fluid concepts and creative analogies: Computer models of the fundamental mechanisms of thought.* New York, NY: Basic Books.

Holyoak, K. J., & Koh, K. (1987). Surface and structural similarity in analogical transfer. *Memory & Cognition, 15,* 332–340.

Holyoak, K. J., & Thagard, P. (1989). Analogical mapping by constraint satisfaction. *Cognitive Science, 13,* 295–355. doi:10.1207/s15516709cog1303_1

Hummel, J. E., & Holyoak, K. J. (1997). Distributed representations of structure: A theory of analogical access and mapping. *Psychological Review, 104,* 427–466. doi:10.1037/0033-295X.104.3.427

James, W. (1890). *The principles of psychology* (Vol. 1*).* New York, NY: Dover.

Jiménez, L., & Méndez, C. (1999). Which attention is needed for implicit sequence learning? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25,* 236–259. doi:10.1037/0278-7393.25.1.236

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, inference and consciousness.* Cambridge, England: Cambridge University Press.

Kaminski, J. A., Sloutsky, V. M., & Heckler, A. F. (2008, June 2). The advantage of abstract examples in learning math. *Science, 320,* 454–455. doi:10.1126/science.1154659

Keane, M. T., Ledgeway, T., & Duff, S. (1994). Constraints on analogical mapping: A comparison of three models. *Cognitive Science, 18,* 387–438. doi:10.1207/s15516709cog1803_2

Kempton, W. (1986). Two theories of home heat control. *Cognitive Science, 10,* 75–90. doi:10.1207/s15516709cog1001_3

Landy, D., & Goldstone, R. L. (2007). How abstract is symbolic thought? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 720–733. doi:10.1037/0278-7393.33.4.720

Leech, R., Mareschal, D., & Cooper, R. (2008). Analogy as relational priming: A developmental and computational perspective on the origins of a complex cognitive skill. *Behavioral and Brain Sciences, 31,* 357–378. doi:10.1017/S0140525X08004469

Markman, A. B., & Gentner, D. (1993). Structural alignment during similarity comparisons. *Cognitive Psychology, 25,* 431–467. doi:10.1006/cogp.1993.1011

Mayr, U. (1996). Spatial attention and implicit sequence learning: Evidence for independent learning of spatial and nonspatial sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 350–364. doi:10.1037/0278-7393.22.2.350

Milner, B., Corkin, S., & Teuber, H. L. (1968). Further analysis of the hippocampal amnesic syndrome: 14-year follow-up study of H. M. *Neuropsychologia, 6,* 215–234. doi:10.1016/0028-3932(68)90021-3

Nersessian, N. J. (1999). Model-based reasoning in conceptual change. In L. Magnani, N. J. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 5–22). New York, NY: Kluwer Academic/Plenum Press.

Nokes, T. J., & Ash, I. K. (2010). Investigating the role of instructional focus in incidental pattern learning. *Journal of General Psychology, 137,* 84–113. doi:10.1080/00221300903352125

Novick, L. (1988). Analogical transfer, problem similarity, and expertise. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 510–520. doi:10.1037/0278-7393.14.3.510

Novick, L. R., & Holyoak, K. J. (1991). Mathematical problem solving by analogy. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 398–415. doi:10.1037/0278-7393.17.3.398

Pearl, J. (2000). *Causality: Models, reasoning, and inference.* Cambridge, England: Cambridge University Press.

Pedone, R., Hummel, J. E., & Holyoak, K. J. (2001). The use of diagrams in analogical problem solving. *Memory & Cognition, 29,* 214–221.

Perfetto, G. A., Bransford, J. D., & Franks, J. J. (1983). Constraints on access in a problem solving context. *Memory & Cognition, 11,* 24–31.

Perruchet, P., Chambaron, S., & Ferrel-Chapus, C. (2003). Learning from implicit learning literature: Comment on Shea, Wulf, Whitacre, and Park (2001). *Quarterly Journal of Experimental Psychology, 56*A, 769–778.

Perruchet, P., & Pacteau, C. (1990). Synthetic grammar learning: Implicit rule abstraction or explicit fragmentary knowledge? *Journal of Experimental Psychology: General, 119,* 264–275. doi:10.1037/0096-3445.119.3.264

Ratterman, M. J., & Gentner, D. (1998). More evidence for a relational shift in the development of analogy: Children's performance on a causal-mapping task. *Cognitive Development, 13,* 453–478. doi:10.1016/S0885-2014(98)90003-X

Reber, A. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and Verbal Behavior, 6,* 855–863. doi:10.1016/S0022-5371(67)80149-X

Reber, A. (1976). Implicit learning of synthetic languages: The role of instructional set. *Journal of Experimental Psychology: Human Learning and Memory, 2,* 88–94. doi:10.1037/0278-7393.2.1.88

Reber, P. J., Knowlton, B. J., & Squire, L. R. (1996). Dissociable properties of memory systems: Differences in the flexibility of declarative and nondeclarative knowledge. *Behavioral Neuroscience, 110,* 861–871. doi:10.1037/0735-7044.110.5.861

Reed, S. K., Ernst, G. W., & Banerji, R. (1974). The role of analogy in transfer between similar problem states. *Cognitive Psychology, 6,* 436–450. doi:10.1016/0010-0285(74)90020-6

Ripoll, T., Brude, T., & Coulon, D. (2003). Does analogical transfer involve a term-to-term alignment? *Memory & Cognition, 31,* 221–230.

Ross, B. H. (1984). Remindings and their effect in learning a cognitive skill. *Cognitive Psychology, 16,* 371–416. doi:10.1016/0010-0285(84)90014-8

Ross, B. H. (1987). This is like that: The use of earlier problems and the separation of similarity effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* 629–639.

Schooler, J. W., & Engstler-Schooler, T. Y. (1990). Verbal overshadowing of visual memories: Some things are better left unsaid. *Cognitive Psychology, 22,* 36–71. doi:10.1016/0010-0285(90)90003-M

Schunn, C. D., & Dunbar, K. (1996). Priming, analogy, and awareness in complex reasoning. *Memory & Cognition, 24,* 271–284.

Shanks, D. R. (2005). Implicit learning. In K. Lamberts & R. L. Goldstone (Eds.), *Handbook of cognition* (pp. 202–220). London, England: Sage.

Shanks, D. R., & St. John, M. F. (1994). Characteristics of dissociable human learning systems. *Behavioural and Brain Sciences, 17,* 367–395. doi:10.1017/S0140525X00035032

Shea, C. H., Wulf, G., Whitacre, C. A., & Park, J.-H. (2001). Surfing the implicit wave. *Quarterly Journal of Experimental Psychology, 54*A, 841–862. doi:10.1080/02724980042000381

Spellman, B. A., Holyoak, K. J., & Morrison, R. G. (2001). Analogical priming via semantic relations. *Memory & Cognition, 29,* 383–393.

Talmy, L. (1988). Force dynamics in language and cognition. *Cognitive Science, 12,* 49–100. doi:10.1207/s15516709cog1201_2

Uttal, D. H., Liu, L. L., & DeLoache, J. S. (1999). Taking a hard look at concreteness: Do concrete objects help young children learn symbolic relations? In C. S. Tamis-LeMonda (Ed.), *Child psychology: A handbook of contemporary issues* (pp. 177–192). Philadelphia: PA: Psychology Press.

Vokey, J. R., & Brooks, L. R. (1992). Salience of item knowledge in learning artificial grammars. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 328–344. doi:10.1037/0278-7393.18.2.328

Waldmann, M. R., Cheng, P. W., Hagmayer, Y., & Blaisdell, A. P. (2008). Causal learning in rats and humans: A minimal rational model. In N. Chater & M. Oaksford (Eds.), *The probabilistic mind: Prospects for Bayesian cognitive science* (pp. 453–484). Oxford, England: Oxford University Press.

Weisberg, R. W., DiCamillo, M., & Phillips, D. (1978). Transferring old associations to new problems: A non-automatic process. *Journal of Verbal Learning and Verbal Behavior, 17,* 219–228. doi:10.1016/S0022-5371(78)90155-X

Wharton, C. M., Holyoak, K. J., Downing, P. E., Lange, T. E., Wickens, T. D., & Melz, E. R. (1994). Below the surface: Analogical similarity and retrieval competition in reminding. *Cognitive Psychology, 26,* 64–101. doi:10.1006/cogp.1994.1003

Wolff, P. (2007). Representing causation. *Journal of Experimental Psychology: General, 136,* 82–111. doi:10.1037/0096-3445.136.1.82

Wood, G., Nuerk, H.-C., Willmes, K., & Fischer, M. H. (2008). On the cognitive link between space and number: A meta-analysis of the SNARC effect. *Psychology Science Quarterly, 50,* 489–525.

Zorzi, M., Priftis, K., & Umilta, C. (2002, May 9). Neglect disrupts the mental number line. *Nature, 417,* 138–139. doi:10.1038/417138a

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