The Role of Diagrams and Diagrammatic Affordances in Analogy

David Latch Craig (david.craig@arch.gatech.edu)
College of Architecture, Georgia Institute of Technology
Atlanta, GA 30332-0155 USA

Nancy J. Nersessian (nancyn@cc.gatech.edu)
College of Computing, Georgia Institute of Technology
Atlanta, GA 30332-0280 USA

Richard Catrambone (rc7@prism.gatech.edu)
School of Psychology, Georgia Institute of Technology
Atlanta, GA 30332-0170 USA

Abstract

We argue that problem solvers can, in certain cases, solve target problems by transforming perceptual simulations of solutions to analogous source problems. We further argue that source diagrams may facilitate the process, but only if they convey physical affordances consistent with the necessary transformations. We conducted an exploratory study in which participants were asked to solve a source and a target problem. We identified two properties of extemporaneously drawn source diagrams – view and configuration – that were highly correlated with the production of analogous solutions to the target problem. We speculated that view and configuration influenced the ease with which certain simulated transformations were performed. The results of two additional experiments in which the view and configuration of source diagrams were independently controlled further support the claim.

Introduction

In this paper we explore the functioning of diagrams in analogical problem solving. Specifically, we investigate how contextual aspects of diagrams – things ranging from depicted physical details to intrinsic properties like perspective, orientation and scale – might afford the kind of simulated physical transformations needed to convert a solution to one problem into a solution to another. In the next two sections we briefly outline our claims concerning diagrams, simulations and affordances, and how they might relate to analogy. In the remaining sections we present the findings of three experiments designed to both illustrate and test those claims.

Diagrams, Simulations and Affordances

One way external diagrams can function in problem solving is by scaffolding perceptual, or analog, simulations in the perceptual and motor cortices of the brain (Barsalou, 1999; Glenberg, 1997). Perceptual simulations have been found to facilitate spatial reasoning (e.g., Kosslyn, 1994) as well as various forms of conceptual reasoning (e.g., Barsalou, Solomon & Wu, 1999; Glenberg & Robertson, 2000; Stanfield & Zwaan, 2001; Fincher-Keifer, 2001). They could potentially benefit problem solving by facilitating the testing and general exploration of candidate solutions.

We argue that the way a diagram is drawn affects not only what is perceptually simulated but also how the resulting simulation can be perceptually transformed. A long history of findings, dating back to Cooper and Shepard's (1973) chronometric studies of mental rotation, support the basic premise that simulations are transformed through simulated motor activity. More recently, researchers have found that simulated transformations are motorically structured and constrained. The ease with which imagined body parts are mentally rotated, for example, parallels the ease with which those parts can be rotated in actuality (Parsons, 1987). In addition, concurrent motor activity consistent with simulated transformations of imagined objects tends to make those transformations faster and more accurate, while inconsistent activities produce interference (Wexler, Kosslyn & Berthoz, 1998). Generally speaking, simulated transformations appear to be constrained in the same way real interaction with the physical world is constrained. Insofar as contextual aspects of diagrams would help determine the physical properties of simulated objects (e.g., texture, shape, mass, etc.) and the context in which they are perceived (e.g., perspective, orientation, scale, etc.), those aspects act as transformational affordances by facilitating certain simulated transformations and inhibiting others.

A finding that illustrates the idea that diagrams convey transformational affordances comes from a study by Schwartz and Black (1996) in which people were shown a diagram of two gears meshed together, one larger than the other, and asked whether two marks, one on the circumference of each gear, would eventually line up if the gears were rotated. By comparing response times against the initial angular disparity of the marks, Schwartz and Black were able to identify different strategies used to complete the task, one of which appeared to be perceptually simulating the two gears rotating together. Ultimately, Schwartz and Black were able to constrain the strategy people used by manipulating the gear diagrams. In particular they found that the simulated-rotation strategy was most likely to be used when the contacting surfaces of the gears were depicted as rough rather than smooth, as if roughness made it easier to imagine one gear driving the other. In this case a physical property depicted in the diagram appears to have affected the ease with which associated perceptual simulations were subsequently transformed.

Analogical Problem Solving

In analogical problem solving, problem solvers start with a solved “source” problem that is similar in some way to an unsolved “target” problem. If a problem solver is aware that the two are related, he or she will need to map the source problem onto the target, thus identifying which problem elements and constraints are identical, which are comparable, and which are irrelevant. Ideally, a mapping will be formed that allows the problem solver to transfer additional aspects of the source to the target, producing a target solution. Although most accounts of analogy are based on perceptually neutral representations (e.g., Gentner, 1983; Gick and Holyoak, 1983), we argue that people can, in certain situations, perceptually simulate source solutions and transform the simulations into solutions to target problems. Following the hypothesis presented in the previous section, we further argue that affordances associated with source diagrams might influence the likelihood that an analogical solution is produced by constraining what transformations can be executed.

Experiment 1

To explore how diagrams influence analogical problem solving we devised an open-ended experiment in which participants were given two superficially dissimilar but analogous problems and asked to 1) consider possible links between them, 2) list whatever similarities they found, and 3) try to solve them. The first problem was written to be easier than the second, the hope being that participants would solve it and thus have a source they could apply to the second problem. No independent variables were controlled. Instead, variations in solutions to the easier problem – in particular variations in the contextual aspects of spontaneously produced sketches – were analyzed after the fact. Correlations between various contextual properties and the production of analogous solutions to the harder problem were then sought.

The easier of the two problems – the one written to be a potential source for the harder problem – involved designing a door system for a laboratory that would give workers free access to the lab space while keeping the air outside the lab from contaminating the air inside. It was assumed that most participants would come up with a redundant-door solution, one that involved either two sets of doors on either side of a vestibule or a revolving door. The harder problem – the one written to be the target – involved designing a pole that suspended a device several feet off the side of a truck. The pole was described as sticking out in such a way that it ran into signposts on the side the of the road (Figure 1). The problem was to design the pole so that it could pass through signposts at a right angle. Ideally, if participants came up with a redundant-door solution to the door problem they would use it to come up with a redundant-pole solution to the pole problem. They might, for example, specify two poles, one that moved out of the way while the other stayed in place and vice versa.

To form an analogy between the door problem and the pole problem requires overcoming not only superficial differences (e.g., differences in objects and object attributes) but also a key structural difference in their respective perceptual contexts. In the door problem, passing through the door is natural; the problem is that it lets bad air in and good air out. In the pole problem, by contrast, passing one object through the other is not natural, and the problem is to make it so. Furthermore, the pole problem involves modifying the thing in motion, while the door problem involves modifying the thing being passed through. Thus, to map a simulated redundant-door solution onto the pole problem ultimately requires a shift in one’s physical frame of reference. One must either 1) imagine that the sign post in the pole problem is the lab worker in the door problem, or 2) imagine that the lab boundary in the door problem is the pole in the pole problem. The latter means imagining an otherwise rooted lab boundary in motion, while the former means imagining an otherwise rooted sign post in motion.

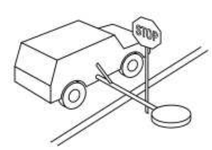

Figure 1 The pole problem: Participants are asked to design a pole that can pass through a signpost.

Transforming the motional context of a simulated redundant-door solution may not be easy. Such a shift might depend on what sort of transformational affordances are present, which might, in turn, depend on the contextual properties of an external diagram. We argue that a diagram of a redundant-door solution might, by scaffolding a perceptual simulation, facilitate the use of such a solution in solving the pole problem, but only if the contextual properties of the diagram afford the shift in motional context required to align the two problems.

Materials and Procedure

The experiment was administered in booklet form. The door problem was printed at the top of the first page and the pole problem just below it. Instructions on the first page asked participants to write down as many similarities between the two problems as they could in 4 minutes. The second page of the booklet was divided vertically, the top containing instructions asking participants to write down a solution to the door problem, the bottom containing instructions asking participants to write down a solution to the pole problem. The instructions specified that they would have 5 minutes total. As participants were led through the booklet they were reminded to carefully read the instructions before starting each task. When they turned to the second page they were verbally told they could draw pictures if it helped them articulate their solutions.

Participants

Two hundred and nine participants were recruited from an introductory psychology class at Georgia Tech to participate in exchange for class credit. The experiment was administered in one large group during a regularly scheduled class session.

Results and Discussion

We first analyzed similarities participants reported prior to solving the problems. Most participants reported superficial similarities, such as that both problems involved engineers. A few also reported highly abstract similarities, such as that both problems involved an obstacle that prevented a device from working. More interestingly, some participants reported that both problems involved something passing through a solid barrier. Although the requirement that something pass through a barrier is clearly stated in the pole problem, it is not stated at all in the door problem. The objective in the door problem is, in fact, opposite that of the pole problem: Something with a penetrable (as opposed to solid) boundary needs to be redesigned to prevent something from getting through (as opposed to allow something through). Despite the implicit nature of the pass-through similarity, 60 of the 209 participants (29%) reported it.

We next analyzed solutions produced for the two problems. Solutions to the door problem were classified as either redundant-door solutions or non-redundant-door solutions, the former being those that included one or more of the following: 1) a verbal reference to two doorways, 2) a verbal reference to an airlock, 3) a verbal reference to a revolving door, 4) a diagram showing two doorways, 5) a diagram showing an airlock, or 6) a diagram showing a revolving door. As expected most participants (184, or 88%) produced some kind of redundant-door solution.

Fewer students, by contrast, were successful in solving the pole problem. Solutions to the pole problem were first classified as either analogous to the door problem or non-analogous. Analogous solutions were those that made use of redundancy. Specifically, a solution was deemed analogous if one part remained in place while another part moved out of the way and vice versa. Such solutions included those with multiple latches (with one latch opening at a time), multiple poles (with one pole retracting at a time), or rotating devices (with one end swinging out of the way as the other end swung into place). Of the 209 participants, 33 (16%) produced analogous solutions to the pole problem. An example of an analogous solution is shown alongside a non-analogous solution in Figure 2

Not surprisingly, participants were more likely to generate an analogous solution to the pole problem if they generated a redundant-door solution to the door problem. Of the 184 participants who generated redundant-door solutions, 31 (17%) produced analogous solutions to the pole problem, while only 2 of the other 25 participants (8%) produced them. Analogous solutions to the pole problem were also correlated with the reporting of pass-through similarities. Of the 60 participants who reported pass-through similarities, 17 (28%) produced analogous solutions to the pole problem, compared to 16 of the 149 (11%) who did not.

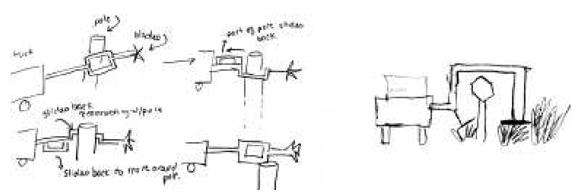

Figure 2 A solution to the pole problem that is analogous to a redundant-door solution to the door problem (left) and one that is not (right).

The remaining analyses concern the diagrams participants drew to illustrate their solutions to the door problem. Of the 184 participants who produced redundant-door solutions, 131 drew at least one diagram. Diagrams alone were not correlated with analogous solutions to the pole problem. Of the 131 who drew diagrams, 22 (17%) produced analogous solutions to the pole problem, while 9 of the remaining 53 participants (17%) also produced them. This is not inconsistent with the argument made earlier about the role of diagrams in problem solving. Of interest is not whether diagrams in general help but whether certain types of diagrams are more highly correlated with the production of analogous solution than others.

To roughly classify diagrams according to transformational affordances we looked at two diagram properties: view and configuration. View was coded as either plan (viewed from above), elevation (viewed from the side), perspective, or ambiguous (either plan or elevation). Configuration was more varied. After reviewing all redundant-door diagrams, 17 distinct configuration types were identified based on the spaces that were depicted and their organization. From these 17 types, two higher-level categories were defined: 1) single-space diagrams, or those in which the only space depicted was the space between the redundant doors and 2) multiple-space diagrams, or those in which additional spaces were depicted. A space, in this case, was defined as any convex area bounded by at least three walls. An example of each type is shown in Figure 3.

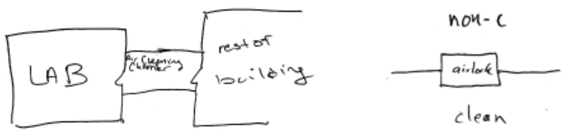

Figure 3 A multiple-space diagram of a redundant-door solution (left) and a single-space diagram (right).

Participants who drew single-space diagrams were significantly more likely to produce analogous solutions to the pole problem than those who drew multiple-space diagrams. Of the 131 participants drawing redundant-door diagrams 26 drew single-space diagrams, and of those 12 (46%) produced analogous solutions to the pole problem. By contrast, only 10 of the 105 (10%) participants who drew multiple-space diagrams produced analogous solutions. The percentage of participants who produced analogous solutions to the pole problem in each of the two main configuration types is listed in Table 1.

Participants who drew diagrams in plan were also much more likely to produce analogous solutions to the pole problem than those who drew diagrams from other views. Of the 131 participants who drew redundant-door diagrams, 58 drew diagrams in plan, 14 (24%) of whom went on to produce an analogous solution to the pole problem. Of the 73 who drew redundant-door diagrams from other views, only 8 (11%) produced analogous solutions. The percentage of participants who produced analogous solutions to the pole problem in each view is listed in Table 2.

Table 1 Number of redundant-door diagrams drawn in each configuration type, and the percentage of those followed by an analogous solution to the pole problem.

	N	Analogous solutions
Single-space	26	46%
Multiple-space	105	10%
N	131	17%

Table 2 Number of redundant-door diagrams drawn in each view, and the percentage of those followed by an analogous solution to the pole problem.

	N	Analogous solutions
Plan	58	24%
Elevation	42	10%
Perspective	22	9%
Ambiguous	9	22%
N	131	17%

There are at least two explanations for why participants were less likely to produce analogous solutions to the pole problem when drawing multiple-space diagrams than when drawing single-space diagrams. One is that additional spaces meant that there were additional unalignable features in the source that could have interfered with a successful mapping. Although this possibility is hard to assess, it should be noted that there were a number of other randomly distributed unalignable features in the diagrams that could have countervailed those associated with multiple spaces.

A second explanation, and one that is more in line with our original hypothesis, is that additional spaces made it more difficult to transform a perceptual simulation of a redundant-door solution into a perceptual simulation of a redundant-pole solution. This explanation rests on three assumptions: first, that the diagrams scaffolded simulations of physical objects with particular transformational affordances; second, that using a redundant-door solution to solve the pole problem required imagining the door system in motion; and third, that a simulated door system might have been rooted via a kinesthetic sense of inertia that would make it difficult to imagine motion. If so, whether a redundant-door diagram facilitated the production of an analogy would have depended on the diagram's affordances. Specifically, the depiction of additional spaces could have caused the door system to seem more physically encumbered and hence harder to simulate in motion as required for a successful mapping.

The fact that view was also correlated with the production of analogous solutions to the pole problem further supports the idea that diagrams both scaffolded and constrained perceptual simulations. Participants, for example, would have likely been able to visualize doors swinging open more easily in plan than in other views (the motion being orthogonal to such a view), making it easier to simulate the actions needed to solve the pole problem. In addition, plan-view simulations may have been more easily transformed because they were not constrained by gravitational affordances, gravity being orthogonal to spatial relations depicted in plan view (Franklin and Tversky, 1990; Rock, 1973). The idea that view and configuration may have influenced perceptually simulated transformations is, of course, speculative. The next two experiments attempt to provide more support for the claim.

Experiment 2

One of the findings from Experiment 1 was that the configuration of source diagrams was correlated with the production of analogous solutions to a target problem. We argued that the diagrams scaffolded perceptual simulations, which could have then been transformed to fit the physical context of the target problem if the diagrams afforded those transformations.

Although Experiment 1 helped illustrate this argument, the analysis was primarily post hoc. The experiment discussed in this section is designed to test the claim in a more controlled way.

A two-condition variation of Experiment 1 was designed. Participants in both conditions were given the door problem with a redundant-door solution already specified and a diagram illustrating it. They were then given the pole problem and asked to solve it, along with the hint that the solution to the door problem might help them. The independent variable was the type of diagram shown with the door problem, while the dependent variable was the type of solution participants produced for the pole problem.

In one condition (the afforded condition) participants were given a redundant-door diagram showing a door vestibule bisecting a wall bounding the lab. In the other condition (the unafforded condition) participants were given a diagram showing the same door vestibule abutting the wall (Figure 4). The number and type of elements were the same in both diagrams, ensuring that differences in performance could not be attributed to differences in the number or type of unalignable objects. Although both diagrams are single-space configurations according to the coding scheme used in Experiment 1, they differ in their physical affordances, particularly in how the vestibule is perceived in relation to the wall. In the afforded condition, the wall and the vestibule are meant to be perceived as overlapping, following the Gestalt law of continuation. In the unafforded condition, by contrast, the vestibule is meant to be seen as resting up against, or attached to, the wall. The diagram in the unafforded condition should thus be harder to imagine moving because it is encumbered by (or anchored to) the lab space, in turn making it harder to align with the pole problem. Following this reasoning, we predicted that participants in the unafforded condition would be less likely to produce an analogous solution to the pole problem than those in the afforded condition.

Figure 4 Diagrams used in the afforded condition (left) and the unafforded condition (right) of Experiment 2.

Materials and Procedure

The door problem and the pole problem used in Experiment 1 were printed on a single sheet of paper. Just below the door problem was written, "Have workers enter a vestibule space before entering the lab," along with one of the two diagrams shown in Figure 4, depending on the condition. Instructions printed at the top of the page and just below the two problems asked participants to carefully read them and write down a solution to the second one. Participants were given 7 minutes to complete the task.

Participants

Twenty-eight students enrolled in undergraduate psychology classes at Georgia Tech participated in groups of 2 to 6 each, 14 in the afforded condition and 14 in the unafforded condition. All received class credit for participating.

Results and Discussion

Solutions to the pole problem were categorized as either analogous or non-analogous to the door problem using the criteria established in Experiment 1. Of the 14 participants in the afforded condition, 10 (71%) produced analogous solutions, compared to only 5 of 14 participants (36%) in the unafforded condition. As predicted, configuration was a significant predictor of whether participants produced analogous solutions (χ^2=3.82, p<.05). The results are shown in Table 3.

Table 3 Participants producing analogous solutions to the pole problem in Experiment 2.

	Analogous solutions	N
Afforded diagram	71%	14
Unafforded diagram	36%	14

Experiment 3

Another notable finding in Experiment 1 was that participants who drew plan diagrams were more likely than those who drew diagrams from other views to produce analogous solutions to the pole problem. We argued that it was easier to perceptually simulate doors opening in plan and hence easier to simulate the action required to solve the pole problem. We also argued that it might be easier to transform a simulation of a redundant-door solution if the simulation was not perceptually structured in relation to gravity, or, in other words, if all spatial relations were orthogonal to gravity. To test this claim, we repeated Experiment 2 with two new redundant-door diagrams: one drawn from the side (unafforded condition) and one drawn from above (afforded condition) (Figure 5). Consistent with the arguments put forth in Experiment 1, we predicted that participants in the afforded condition would be more likely to produce an analogous solution to the pole problem.

Figure 5 Diagrams used in the afforded condition (left) and unafforded condition (right) of Experiment 3.

Materials and Procedure

The same materials and procedure used in Experiment 2 were used except that the diagrams accompanying the redundant-door solution were either elevation or plan diagrams, depending on the condition (Figure 5).

Participants

Twenty-two students enrolled in undergraduate psychology classes at Georgia Tech participated in groups of 2 to 6 each, 11 in the afforded condition and 11 in the unafforded condition. All received class credit for participating.

Results and Discussion

Solutions to the pole problem were categorized as either analogous or non-analogous to the door problem, using the criteria established in Experiment 1. Of the 11 participants in the afforded condition, 7 (64%) produced analogous solutions, compared to only 2 of the 11 participants (18%) in the unafforded condition. Consistent with our prediction, diagram view was thus a significant predictor of whether participants produced analogous solutions (χ^2=5.43, p<.05). The results are shown in Table 4.

Table 4 Participants producing analogous solutions to the pole problem in Experiment 3.

	Analogous solutions	N
Afforded diagram	64%	11
Unafforded diagram	18%	11

Conclusions

The studies reported here begin to shed light on what might make a diagram useful for constructing an analogy. They results strongly suggest that aspects of diagrams like view and configuration can influence the ease with which diagrammed solutions can be used to solve analogous problems, possibly by regulating simulated transformations. The studies also lend support to the more general idea that analogies can be constructed via perceptual simulations, as opposed to predicate-based, or otherwise perceptually neutral, representations. And finally, although just a start, the results reported here help illustrate an expanded role for drawings as cognitive tools. Drawings might now be seen not only as a means for recording ideas for future reference but also as a means for exploring the transformational affordances of problem spaces in search for those that will ultimately lead to more promising solution paths. Problem solvers might, from this point of view, actually learn to manipulate problem spaces via diagrammatic affordances just as they might learn to navigate problem spaces using conventional reasoning strategies.

References

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, 22, 577-609.

Barsalou, L. W., Solomon, K. O., & Wu, L. L. (1999). Perceptual simulation in conceptual tasks. In M. K. Hiraga, C. Sinha, & S. Wilcox (Eds.), *Cultural, typological, and psychological perspectives in cognitive linguistics: The proceedings of the 4th conference of the International Cognitive Linguistics Association,* (209-228). Amsterdam: John Benjamins.

Cooper, L. A., & Shepard, R. N. (1973). The time required to prepare for a rotated stimulus. *Memory & Cognition*, 1, 246-250.

Fincher-Kiefer, R. (2001). Perceptual components of situation models. *Memory & Cognition*, 29, 336-343.

Franklin, N., & Tversky, B. (1990). Searching imagined environments. *Journal of Experimental Psychology: General,* 119, 63-76.

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

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology,* 15, 1-38.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences,* 20, 1-19.

Glenberg, A. M., & Robertson, D. A. (2000). Symbol grounding and meaning: A comparison of high-dimensional and embodied theories of meaning. *Journal of Memory & Language*, 43, 379-401.

Kosslyn, S. M. (1994) *Image and Brain*. Cambridge, MA: MIT Press.

Parsons, L. M. (1987). Imagined spatial transformation of one's body. *Journal of Experimental Psychology: General*, 116, 172-191.

Rock, I. (1973). *Orientation and Form*. New York: Academic Press.

Schwartz, D. L., & Black, J. B. (1996). Analog imagery in mental model reasoning: Depictive models. *Cognitive Psychology*, 30, 154-219.

Stanfield, R. A., & Zwaan, R. A. (2001). The effect of implied orientation derived from verbal context on picture recognition. *Psychological Science*, 121, 153-156.

Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition*, 68, 77-94.