

Pictorial and Verbal Tools for Conveying Routes

Barbara Tversky and Paul U. Lee

Stanford University Department of Psychology, Bldg. 420
Stanford, California 94305-2130 USA
email: bt, pauly @psych.stanford.edu

Abstract. Traditionally, depictions and descriptions have been seen as complementary; depictions have been preferred to convey iconic or metaphorically iconic information whereas descriptions have been preferred for abstract information. Both are external representations designed to complement human memory and information processing. We have found the same underlying structure and semantics for route maps and route directions. Here we find that limited schematic map and direction toolkits are sufficient for constructing directions, supporting the possibility of automatic translation between them.

Keywords: diagrams, directions, external representation, map, route

1 Introduction

Traditionally, depictions and descriptions have been seen as complementary; depictions are good at conveying one kind of information and descriptions another. Pictures are often regarded as an iconic medium, representing real objects and real space by similarity to them, though this view is emphatically denied by many (e. g., Goodman, 1968). Diagrams, a kind of depiction not meant to represent the physically apparent world, uses objects and space metaphorically to represent elements and relations among them (e. g., Tversky, in press; Winn, 1989). By contrast, language is seen as a purely symbolic medium that conveys meaning through arbitrary symbols combined in complex, rule-governed structures. Depictions, then, are regarded as more appropriate for information that is directly or metaphorically visualizable, whereas descriptions are regarded as more appropriate for abstract information.

In actual practice, graphic and verbal media are rarely pure. Maps, for example, typically have legends and some arbitrary symbols, such as those for towns of specified populations or those for industrial production or historic sites. On the verbal side, written language uses a variety of spatial devices, such as spaces between words or indentations for paragraphs, that convey use physical space to convey meaning metaphorically.

1.1 External Representations

Information Processing Advantages. Yet, when on paper, both pictures and words are external representations, cognitive tools invented to promote memory or thinking. As Donald (1991) puts it, external representations are analogous to internal ones; they are storage and retrieval devices. But external devices have certain advantages (and disadvantages) that internal ones don't have. Their advantages have been highlighted by a number of researchers in a number of contexts: by Larkin and Simon (1987) in diagrammatic reasoning, by Donald (1991) in evolution of mind, by Norman (1993) and Scaife and Rogers (1996) in human-computer interaction, and by Kirsh (1996) in everyday activities. The utility of external representations derives from the interaction of their external format with qualities of information processing. Good external displays compensate for limitations of information processing while taking advantage of skills of information processing. Whereas human information processing is limited, both in number of items (memory) and in number of operations (processing), external representations are virtually unlimited, though searching through them can be costly. Whereas information processing is fleeting, external representations are permanent. Whereas human information processing is a private, internal event, external representations are public, transportable, and sharable. External representations enlarge human memory and enhance processing by offloading those burdens from the mind to inspectible, rearrangeable space. People are limited in the amount of information and mental operations that they can keep track of, but people are excellent at pattern recognition. Turning internal information and operations into external patterns augments the powers of mind.

Special Features of Depictions. As external representations, depictions are thought to have unique advantages. The arrangement of items in space in and of itself facilitates cognitive activity. For example, related information may be spatially proximal, minimizing search and facilitating inferences (Larkin & Simon, 1987; Suwa & Tversky, 1997). Spatial arrangements themselves are meaningful. Grouping, ordering, and distance in space correspond to grouping, ordering, or distance on some other dimension (Tversky, 1995). To save time cooking for instance, chefs line up ingredients in the order of use (Kirsh, 1995). In diagrams of mechanical or social systems, the spatial arrangement of components represents causal relations or information flow (e. g., Kieras, 1992). In typical X-Y graphs, order and interval on each of the axes represent order and interval on dimensions such as time and money.

Limitations of Depictions. The very specificity that makes depictions tractable to search and inference limits their expressiveness (e. g., Stenning & Oberlander, 1995). Without introducing arbitrary notation, it is difficult to convey abstract concepts such as justice and freedom or relations such counterfactual and hypothetical pictorially. Thus, the effectiveness of depictions comes from their use of space in meaningful ways and their ease in making inferences. However, depictions force concreteness where it may not be meaningful, encouraging false inferences. As Bishop Berkeley long ago noted, one can only depict a particular triangle, with specific angles

and sides, not a general, abstract triangle. Depictions may convey some concepts naturally, but they don't naturally convey other meanings and relations.

2 Route Maps and Directions

2.1 Structure of Route Directions

One common arena where depictions and descriptions are used interchangeably is in conveying route instructions, in directing others how to get from point A to point B. Denis and his collaborators (Denis, 1997; Denis & Briffault, 1997; Denis, Pazzaglia, Cornoldi, & Bertolo, 1998) have analyzed the structure of verbal route directions collected in the field in locales as disparate as a French university campus and Venice. Based on quality ratings by judges on a large corpus of directions, Denis (1997) discerned several components of ideal route directions. These components may overlap in the same utterance and they may be implicit. The first step is to put the listener at the point of departure. In the field, this is typically apparent to both interlocutors and need not be specified. The second step, beginning the progression, may also be implicit. The next three steps are used iteratively until the goal is reached: designate a landmark; reorient the listener; start the progression again by prescribing an action. Actions may be changes of orientation or continuations in the same direction. The critical information, then, is a sequence of segments, triples designating an orientation, an action, and a landmark. Landmarks are typically the start and end points of each segment, though at least one is usually implicit.

2.2 Route Maps

How do route maps compare to route directions? In order to find out, Tversky and Lee (1998) stopped bypassers near a campus dorm, and asked them if they knew how to get to a popular off-campus fast food restaurant. If they answered affirmatively, they were asked to either sketch a map or write directions to the restaurant. The resulting corpus was diverse, especially for the directions. Some were lists of turns on streets, whereas others were complete sentences with extensive descriptions of landmarks. Two coders coded the maps and directions for Denis' categories, and extra information. In fact, more than 90% of maps and directions contained some extra information, for example, cardinal directions, arrows, distances, extra landmarks, and landmark descriptions. The directions collected by Denis and his collaborators contained similar extra information.

2.3 Common Structure for Directions and Maps

More remarkable was the finding that the structure of route maps was essentially the same as the structure of route directions. Like route directions, route maps could be divided into segments containing starting and ending landmarks, orientations, and actions. Moreover, the semantic content of the elements, whether depicted or described, was similar. The similarity of structure and content suggests that the same conceptual information served as a basis for both depictions and descriptions of routes, and that route depictions and descriptions schematized the real world information in similar ways.

Start and end points in both maps and directions were landmarks, buildings, or roads. These were named in directions, and often in maps as well. In maps, building and field landmarks were often schematized as rough shapes. Actions were indicated in maps by lines, double or single, that referred to paths. In about half the cases, they were accompanied by arrows. Arrows were usually redundant, however, as the route maps, unlike other sketch maps, included only the streets relevant to the traveler, so there was no ambiguity about which path to take. Maps had three kinds of paths, intersections, straight paths, and curved paths, mapping onto the three kinds of actions distinguished in directions. Intersections in maps corresponded to turns in directions. The intersections were drawn at approximately 90 degrees irrespective of the actual angle. Actions directing the traveler to turn were, like the route maps, indifferent to angle of turn. They used terms like "turn," "take a," "make a," "go," or simply "left" or "right." Straight paths in maps corresponded to continuing straight in directions. Actions directing the traveler to continue along a straight road tended to use terms like "go," "head," "continue," and "keep going." Finally, curved paths corresponded to following a curved road in directions. Actions directing the traveler to follow a curved road tended to use "follow" rather than "go." Although route maps are potentially an analog medium, map-makers did not take advantage of the analog feature of depictions. Instead, they discretized the environment in essentially the same way as they did in route directions, treating path curvature, intersections, turns, and so forth, categorically.

2.4 Conclusions

Both maps and directions, then, were composed of the same components, landmarks, orientations, and actions. Moreover, they made similar and corresponding distinctions within each of those categories. Nevertheless, there were interesting differences between maps and directions that seem to derive from their different media, depictive vs. descriptive. For each type of component, there were more verbal options than pictorial. This seems to be due to the iconic character of maps, of depictions of space. Mapping more or less straight roads in the world to more or less straight lines on paper is a natural correspondence (cf. Tversky, 1995). Language allows several different ways to express the same action. A related property of elements of depictions is that they conflate concepts that descriptions often separate. For example, in depictive

tions, a crossed pair of lines indicates an intersection, a start point, an end point, and a turn simultaneously.

The iconic nature of depictions underlies a striking difference between the route maps and the route directions, sufficiency. All of the information necessary for getting from the start point to the destination was explicitly contained in the maps; that is, the maps were sufficient. Viewed superficially, much of the necessary information was missing from the directions. Seventy-five percent of the directions lacked either a start or an end point, and 45% lacked a piece of path/progression information. Yet, for the most part, the route directions appeared to be adequate to allow a traveler to arrive at the destination. Most of the missing information was implicit. Nearly all of it could be inferred by applying two simple inference rules.

The rule of continuity stipulates that if a start point is missing, it is the same as the previous end point, or vice versa. The rule of forward progression stipulates that when two reorientations occur successively, a forward movement is implied between those two reorientations. For example, a direction "Turn left at X St. Turn right at Y St." implies "Turn left at X St. *Go down X St until Y St.* Turn right at Y St." Assuming these inference rules, 86% of directions were complete and sufficient. However, three route directions were missing the direction of a turn. The pragmatics of depictions preclude those sorts of ambiguities. The necessity to be specific, to draw a complete route, insures inclusion of all the needed information. Language, by contrast, allows different ways of expressing the same order of landmarks or sequence of events, by disambiguating using structural terms like "before," "after," and "in front of".

3 Translating Depictions to Descriptions and Descriptions to Depictions

The similarity of structure between route directions and route maps revealed in the analysis of the protocols collected by Tversky and Lee (1998) suggests that it may be possible to automatically translate between them. Both directions and maps are composed of similar components, landmarks, orientations, and actions. Within each class of component, there are correspondences between the depictions and the descriptions, for example, straight lines to "go." A system that translated depictions to descriptions and vice versa would be useful for many situations, including car navigation devices, where digital maps could efficiently store many possible routes and specific routes could be presented verbally to prevent distracting the driver from watching the road. The previous experiment suggested that route maps and route directions are composed of units and segments that are parallel across the media.

Here we report a project that is a preliminary test of the feasibility of automatic translation between depictions and descriptions of routes. We gave participants a set of route-finding problems and provided them with toolkits, depictive or descriptive, to use to construct the routes. Participants were encouraged to supplement the toolkits whenever needed. The toolkits were based on the elements that appeared in the Tver-

sky and Lee (1998) protocols, with some additions to take account of a wider variety of routes. The components of the toolkits were the natural components of each medium, so there was no direct and obvious correspondence between map and direction components. The components of the map toolkit were pictorial elements whereas the components of the direction toolkit were verb phrases. The question of interest is whether the tool kits were at the right level of granularity and rich enough to construct route directions or maps that the creators thought were adequate. If not, the results will reveal how to alter or enhance the tool kits to enable production of adequate route maps and route directions.

3.1 Method

Participants. The participants were 14 Stanford students fulfilling a course requirement.

Tasks. Each participant constructed 7 maps and 7 directions as a block in counter-balanced order. To make sure participants knew the routes, each participant selected the particular routes from a larger set. Each block of 7 consisted of 3 routes from landmark within Stanford campus to a landmark outside campus, 3 routes from an off-campus landmark to an on-campus landmark, and 1 longer route (15 miles or more) off-campus.

Materials. Participants were provided with toolkits on paper and blank paper, a black pen, and a red pen to construct the maps and directions. They were also given scotch tape to create larger maps if needed.

Procedure. Before each block, participants constructed a map or directions as appropriate without the toolkit. Then participants were shown the toolkit and asked to use it to construct the 7 maps or directions. Participants were told that the toolkits were insufficient and that they could supplement them as they saw fit. They were asked to use the black pen for toolkit elements and the red pen for their own additions.

Toolkits. The toolkits were selected to be minimalist. For each segment type, an element was selected for each major common distinction represented in the corpus of the first experiment.

Map Toolkit. The map toolkit appears in Fig. 1. It contained 3 types of intersections, X, T, and L; two types of paths, curved and straight; two types of arrows, bent and straight; and two types of landmarks, rectangles and circles.

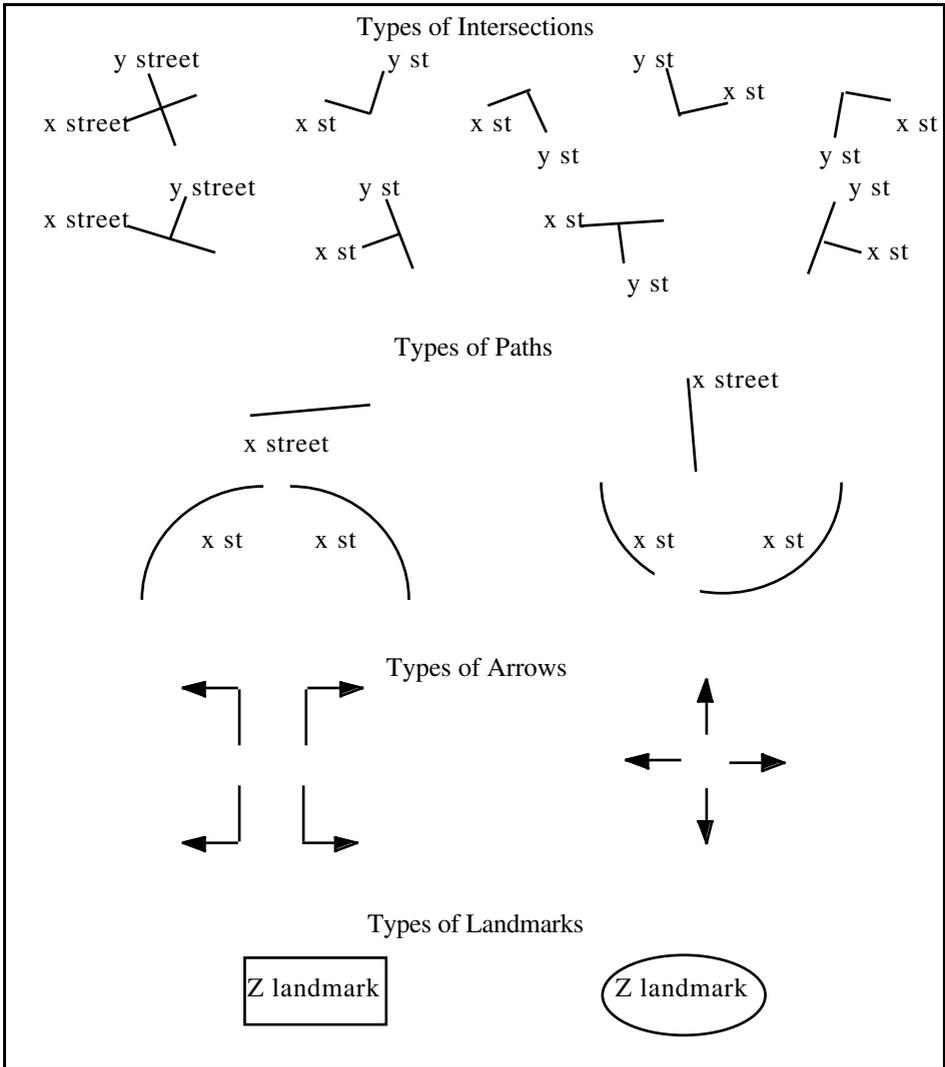


Fig. 1: Map Toolkit

Direction Toolkit. The direction toolkit appears in Fig. 2. It primarily contained verb phrase frame options, with blanks that could be left that way or completed with landmarks, such as path names, buildings, street signs and the like. The opening direction frame was: Start at _____, facing _____. The destination frame was: _____ will be on your [left][right]. The remaining verb phrase frames described actions [turn, go down, follow, continue] with or without respect to landmarks or paths or distance/time.

Types of Direction Phrases	
Start at _____, facing _____.	
Turn left.	
Turn left on _____.	
Turn right.	
Turn right on _____.	
Go down _____.	
Go down until _____.	
Go down _____ until _____.	
Go down _____ for <i>distance or time</i> .	
Follow _____.	
Follow until _____.	
Follow _____ until _____.	
Follow _____ for <i>distance or time</i> .	
Continue past _____.	
_____ will be on your left.	
_____ will be on your right.	
Blanks above are filled with:	
<ul style="list-style-type: none"> • Path names (e.g. X St., Y Ave., etc.) • Buildings/Areas (e.g. Yankee Ballpark, Eiffel Tower, etc.) • Streets and other markers that indicate relative position from the current position (e.g. 1st street on the right, 2nd intersection from here, etc.) • Stop sign or stop light 	

Fig. 2: Direction Toolkit

3.2 Results

Maps: Use of Toolkit Elements. Fig. 3 illustrates a typical map drawn by the participants using the map toolkit, compared to an actual map of the same region. All of the participants used the three types of intersections as well as the straight-line path. The intersection types (i.e. X, T, and L type intersections) were not always veridical; in fact, 93% of participants used at least one incorrect intersection. In some cases, misuse might have been deliberate, a Gricean attempt to simplify the information in the map for the user. For example, an X-intersection might be drawn as a T-intersection because the traveler needs to turn, so doesn't need the information that the road continues straight as well. Eighty-six percent of participants used arrows and

curved paths. Although all participants used both rectangular and round landmarks, the rectangular ones were used as a default, and the round ones in special cases where the landmark was round.

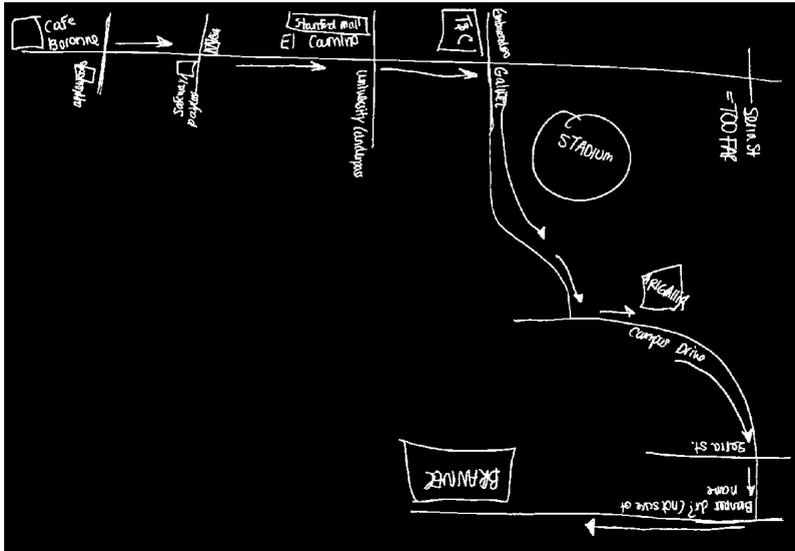


Fig. 3: A map drawn by a participant using the map toolkit and an actual map of the corresponding region

Maps: Added Elements. Participants were told the toolkit was insufficient and were encouraged to supplement it. Since many intersections and paths around Stanford are irregular (see Fig. 3), participants were especially encouraged to denote intersections and curved paths accurately. In spite of this, only 43% of participants marked at least one intersection as differing from 90 degrees and 29% marked at least one path as differing from straight or curved. Moreover, these deviations were not necessarily accurate.

About half of the participants used special depictions for exit ramps overpasses, and street signs or lights. Twenty-one percent of participants used other iconic landmarks and 43% used landmarks that were neither rectangular nor square, but were also not iconic. Half the participants added short descriptive information supplementing the information on paths or landmarks beyond their names. Two used compass directions and one used distance information.

Start at Stanford Shopping Center, facing El Camino.
 Turn right onto El Camino.
 Turn right at the first light onto Galvez St.
At the second stop sign, turn left onto Serra St.
 Follow Serra St. until you hit Campus Dr.
 Turn right onto Campus.
 Turn right at the first stop sign onto Escondido Rd.
 Branner should be on your right side.

Fig. 4: Directions by a participant using the direction toolkit. Underlined phrases are marked by the participants to indicate that they are not provided by the toolkit.

Directions: Use of Toolkit Elements. Fig. 4 illustrates typical directions generated by the participants using the direction toolkit. As for maps, participants used all of the classes of elements provided in the toolkit. Some replaced the given elements with synonyms. The toolkit provided a set of terms for path progression and turns, including "turn," "follow," "go down," and "continue." Some participants omitted some of these, shortening their directions to just turn direction for example. A few other participants substituted synonyms, such as "make a" or "take a." Substitutions were also made in the prepositions or verb particles, "turn at" for "turn on" and "continue through" for "continue past."

Participants did supplement the direction toolkit in a number of ways. Some added some actions; six added "exit" and five added "U-turn." Some added landmarks; one added "overpass," and three added "dead end." Some actions were modified spatially, as in "turn sharply," or temporally, as in "after 3 minutes" or "turn immediately." Although the tool kit frames allowed only one landmark per action, most participants added a second landmark to at least one action. Most participants also provided additional information on the end point, typically additional locative information, such as direction from the traveler and/or some nearby landmark. Altogether, most of the information added was locative.

4 Discussion

4.1 Toolkits for Route Maps and Directions

Were the toolkits sufficient? Both map and direction toolkits contained elements for paths, actions, and landmarks, known from previous research to be the essentials of route directions. Moreover, the elements were schematized so that paths were either straight or curved, actions were continue straight, follow a curved path, or turn, landmarks were rectangles or circles. Arrows were also provided to mapmakers to accentuate the route. With some minor exceptions, these elements were sufficient for constructing route maps, despite the fact that participants were had been told the toolkits were not likely to be sufficient and encouraged to supplement it. Participants had also been encouraged to represent intersections and paths accurately; nevertheless, they did not do so frequently. Even when participants constructed the angle of intersection or curvature of path, they were not necessarily doing so correctly. In constructing maps, some participants invented iconic symbols for common types of landmarks, such as overpasses or lights. These were remarkably similar across participants, suggesting shared graphic schemas. Finally, for maps, some participants added verbal descriptions of landmarks and paths, especially at the goal.

Similarly, for the most part, the toolkit elements were sufficient for constructing route directions. Some participants substituted near synonyms for actions, such as “make a left/right” for “turn left/right”. Some participants added elements for actions or landmarks. Many used an additional landmark to facilitate locating a critical one, especially at the goal.

All of the elements provided by both toolkits were in fact used by most of the participants, suggesting that most or all of them were necessary. One exception might be the arrows, which were in fact used at least once by most participants in this study. However, they were not used consistently in this study and they were spontaneously used by only half the participants in the previous study. The pragmatics of route maps allow inference of path direction from the start and end points and elements of the environment included in the sketch map.

Of course, there is a trade off between the size of the toolkits and their adequacy, though the inconsistency of additions to the toolkits here suggests that the elements and their instantiations offered here were remarkably apt. The inconsistency of additions also suggests diminishing returns with increasingly large toolkits. Moreover, larger toolkits would undoubtedly be more cumbersome to apply in constructing maps and directions.

Would these toolkits be sufficient in general? The toolkits were developed and tested using a city world, where there are clear paths connecting start and end points. Moreover, the paths are usually streets, therefore named. Intersections of paths also serve as landmarks, used to anchor actions. The test indicated that it might be desir-

able to supplement the toolkits with additional landmarks, such as exits and lights, as well as actions, such as U-turns. The number of elements currently in the toolkits is very small, so supplementing them is reasonable and should not impose a burden on users.

Even with these additions, the toolkits would probably not be sufficient for getting from here to there in an environment without clear paths, such as a barren desert or dense jungle. In those cases, however, conventional sketch maps or route directions are also likely to be deficient, and either topological maps supplemented by a compass (or GPS) or a knowledgeable guide might be needed to avoid error.

4.2 Automatic Translation of Maps to Directions and Directions to Maps?

This study can be regarded as what Gleitman (1999) has termed “a simulation of a simulation”. The implicit question is the feasibility of a system to automatically translate maps to directions and vice versa. The study suggests that this may be possible. Both route maps and route directions can be decomposed to the same elements, one set graphic, the other verbal as outlined earlier (see section Common Structure for Directions and Maps). The verbal and graphic elements map onto one another. Toolkits consisting of either the verbal or the graphic elements appear to be sufficient, with some additions, to construct route directions or route maps to get from one place to another in an urban environment.

4.3 Toolkits for Other Domains

For the domain of routes, then, both depictions and descriptions seem to convey equivalent information. There may be reasons to prefer one medium over another in specific situations, such as a verbal medium during car navigation. Are routes unique, or are there other familiar domains where depictions and descriptions are close equivalents? As for routes, such a domain would require a common underlying conceptual structure that naturally decomposes into equivalent graphic and verbal elements. One possibility is the part structure of objects or systems, which can be represented by a diagram or a structural description. In fact, directions for assembling objects or operating systems are often given in either form. Nevertheless, depictions would seem to have an advantage for two reasons: first, the iconicity of parts or elements should facilitate identifying them; second, the spatial relations of parts or elements should be easier to determine from the spatial relations of depictions than from verbal descriptions. Diagrams are known to facilitate comprehension of such systems (e. g., Kieras, 1992; Mayer & Gallini, 1990).

A more abstract domain where depictions and descriptions may be near equivalents is graphs. Zacks and Tversky (in press) have investigated two mirror-image tasks: people's interpretations of the relations depicted in graphs, in particular, bar and line graphs and people's production of graphic depictions from descriptions of relations of data. There was a simple prediction. As graphic elements, lines are like paths, they

connect points. In contrast, bars are like containers, they enclose a set of elements, separating them from other elements. In other words, these graphic elements naturally suggest meanings or interpretations. The expectation was that people would interpret bar graphs as discrete comparisons and line graphs as trends, and conversely, that people would use bars to represent descriptions of discrete comparisons and lines to represent descriptions of trends. These predictions were confirmed. In fact, the effects of the graphic elements were stronger than the effects of the categorical or continuous nature of the underlying variables.

5 Conclusions

The existence of parallel depictions and descriptions for a domain, such as routes, suggests a common conceptual structure underlying both. The conceptual structure consists of a something analogous to semantics, a set of primitives with meanings, and something analogous to syntax, a way to combine meaningful primitives to construct a meaningful whole. In the case of graphs, the meaningful whole is a set of relations among variables or data; in the case of routes, the meaningful whole is a set of directions to get from here to there. Parallel instantiations for depictions and descriptions seem to depend on some natural way of depicting elements of meaning as well as a common conceptual structure. For maps, this is accomplished by elements such as paths and intersections that bear some resemblance to their real world counterparts. For graphs, this is accomplished by elements such as bars and lines that bear some natural conceptual resemblance to their conceptual counterparts. In both cases, the utility of the external representations are reinforced by the social processes underlying establishment of communicative conventions (e. g., Clark, 1992).

The existence of parallel depictions and descriptions for several domains does not imply that both are equally effective in all situations. Instead it is likely that for some inferences and tasks, depictions are more effective but for others, descriptions are to be preferred. And, in fact, as noted earlier, many cases are mixed, such as maps or writing. Ideally, these mixtures simultaneously utilize the relative advantages of both depictions and descriptions.

References

1. Clark, H. H. (1992). *Arenas of language use*. Chicago: University of Chicago Press.
2. Denis, M. (1997). The description of routes: A cognitive approach to the production of spatial discourse. *Cahiers de Psychologie Cognitive*, 16, 409-458.
3. Denis, M. and Briffault, X. (1997). Les aides verbales a l'orientation spatiale. In M. Denis (Editor), *Langue et Cognition Spatiale*. Paris: Masson.
4. Denis, M. Pazzaglia, F., Cornoldi, C., & Bertolo, L. (1998). Spatial discourse and navigation: An analysis of route directions in the city of Venice. *Applied Cognitive Psychology*, 12.
5. Donald, M. (1991). *Origins of the modern mind*. Cambridge: Harvard University Press.

6. Dwyer, F. M. (1978). Strategies for improving visual learning. State College, PA: Learning Services.
7. Gleitman, L (1999). Personal communication.
8. Goodman, Nelson. Languages of Art: An Approach to a Theory of Symbols. The Bobbs-Merrill Company, Inc. 1968, 127-173.
9. Kieras, D (1992). Diagrammatic display for engineered systems : effects on human performance in interacting with malfunctioning systems. *International Journal on Man-Machine Studies*, 36, 861-895.
10. Kirsh, D. (1995). The intelligent use of space. *Artificial Intelligence*, 73, 31-68.
11. Larkin, J. H. and Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11, 65-99.
12. Levie, W. H. and Lentz, R. (1982). Effects of text illustrations: A review of research. *Educational Communication and Technology Journal*, 30, 195-232.
13. Levin, J. R., Anglin, G. J. & Carney, R. N. (1987). On empirically validating functions of pictures in prose. In D. M. Willows and H. A. Houghton (editors). *The psychology of illustration*. NY: Pp. 51-85.. Springer-Verlag.
14. Mayer, R. E. & Gallini, J. K. (1990). When is an illustration worth ten thousand words? *Journal of Educational Psychology*, 82, 715-726.
15. Norman, D. A. (1993) Things that make us smart. NY: Addison-Wesley.
16. Scaife, M. and Rogers, Y. (1996). External cognition: How do graphical representations work? *International Journal of Human-Computer Studies*, 45, 185-213.
17. Stenning, K. and Oberlander, J. (1995). A cognitive theory of graphical and linguistic reasoning: Logic and implementation. *Cognitive Science*, 19, 97-140.
18. Suwa, M. and Tversky, B. (1997). What architects and students perceive in their sketches: A protocol analysis. *Design Studies*, 18, 385-403.
19. Tappe, H. & Habel, C. (1998) Verbalization of dynamic sketch maps: Layers of representation and their interaction. Manuscript.
20. Tversky, B. (1995). Cognitive origins of graphic conventions. In F. T. Marchese (Editor). *Understanding images*. Pp. 29-53. New York: Springer-Verlag.
21. Tversky, B. (In press). Spatial schemas in depictions. In M. Gattis (Editor), *Spatial schemas and abstract thought*. Cambridge: MIT Press.
22. Tversky, B. and Lee, P. U. (1998). How space structures language. In C. Freksa, C. Habel, and K. F. Wender (Editors), *Spatial Cognition: An interdisciplinary approach to representation and processing of spatial knowledge*. Pp. 157-175. Berlin: Springer-Verlag.
23. Winn, W. (1989). The design and use of instructional graphics. In H. Mandl and J. R. Levin (Editors). *Knowledge acquisition from text and pictures*. Pp. 125-143. North Holland: Elsevier.
24. Zacks, J. and Tversky, B. (In press). Bars and lines: A study of graphic communication. *Memory and Cognition*.