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The Perception and Cognition of Environmental Distance: Direct Sources of Information*

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Abstract. Research on direct sources of information for the perception and cognition of environmental distance is reviewed. Environmental distances are relatively large and cannot be perceived in entirety from a single place. Directly-acquired knowledge of environmental distance is based on the sensorimotor apprehension of information from the body or from the environment during locomotion. The paper is organized around the idea that distance knowledge is derived from multiple, partially redundant information sources. After briefly discussing general issues, I review literature on direct sources of distance information, including environmental features, travel time, and travel effort. Theories of how these sources provide information about distance are considered. To date, only information from environmental features has received much empirical support as a direct source of distance knowledge, particularly to the extent that the features segment routes into vistas. Key weaknesses in the empirical literature are discussed, and important research directions are identified.

1 Introduction

Information about distance plays an important role in human activity. It helps us orient ourselves and locate places during navigation. It is used to evaluate costs of traveling from one place to another, and it helps us utilize resources efficiently (time, money, food). Clearly, knowledge of distances in the environment "affects the decision to stay or go...the decision of where to go...[and] the decision of which route to take" (Cadwallader 1976: p. 316). It therefore seems likely that an understanding of the perception and cognition of distance will prove fundamental to the prediction and explanation of spatial behavior.

Because of its important role in spatial activity throughout evolutionary history, understanding distance psychology should inform us about other cognitive structures and processes. An example is the representation of similarity distances in the semantic "spaces" generated by multidimensional scaling. The usefulness of mapping semantic relatedness with such spatial representations may reflect a profound role of spatial cognition in cognitive processes in general.

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The universality of spatial metaphor in language provides another good example (Lakoff 1987).

Geographers, planners, and other researchers of molar human behavior have typically maintained that choices of routes[1] and destinations should reflect the human desire to minimize functional distance (Deutsch and Isard 1961; Golledge and Stimson, 1997). For example, gravity models of human macrospatial behavior, such as migration and shopping trips, incorporate the idea that places farther away invite less interaction because of the "friction" required to overcome greater distances (other things being equal). One attempt to improve these models has been to replace physical distance with subjective distance (Coshall 1985; Thompson 1963). Such an approach could also improve models of route-choice and driving behavior (Brimberg 1992).

It is sometimes argued that metric knowledge of physical distances is not required for navigation and spatial planning. Much spatial choice and behavior could take place on the basis of minimal knowledge about a sequence of landmarks, for instance, or knowledge of travel times. I discuss in detail elsewhere (Montello, in press) conceptual and empirical arguments for the existence and functionality of some quantitative knowledge of physical distance (its precision is another question). Neither minimal sequence knowledge nor temporal knowledge alone are sufficient, for example. Of course, not all coordinated spatial behavior requires metric distance knowledge. Nor are people always explicitly aware of the distance knowledge they use. In such cases, they may still do quite well on behavioral tasks that require only implicit knowledge of distance.

1.1 Environmental Distance Knowledge Acquired Directly

Knowledge of *environmental* distances is discussed in this paper, distances within physical spaces that are larger than the human body and surround it, but not so large that they cannot be apprehended through direct travel experience. Environmental spaces include parks, buildings, campuses, neighborhoods, and cities. Apprehension of such spaces is usually thought to require the integration of knowledge over significant periods of time. For this reason, environmental distance knowledge has traditionally been labeled *cognitive distance* (Canter and Tagg 1975). In contrast, knowledge of distances to objects or places visible from a single location has been labeled *perceptual distance* (Baird 1970). I do not use these terms in the present manuscript; they are somewhat misleading insofar as perceptual and cognitive processes (or bottom-up and top-down, etc.) are involved in both types of distance knowledge.

I concentrate on distance knowledge directly acquired while locomoting through environments. Thus, some perception or awareness of body movement or change of position must be involved, whether valid or not. I do

[1]A useful distinction can be made between *routes* as locomotion patterns and *paths* as physical features in the world (streets, trails). There are many possible routes within a given path network, for instance, or routes are traveled where there are no paths.

not consider *symbolic sources* of distance knowledge in detail, such as maps, road signs, odometers, and verbal directions. Of course, under normal conditions, such sources certainly provide information about environmental distances and thus influence knowledge acquired via direct experience (or preclude the need for learning via direct experience). The integration of spatial information from multiple sources, both direct and indirect, is an important area for research (Montello and Freundschuh 1995).

A classic example of research on geographic spaces in which map knowledge is undoubtedly involved is that of Ekman and his colleagues on emotional involvement and subjective interurban and international distances (e.g., Ekman and Bratfisch 1965). Although interesting, it is questionable whether these studies tell us much about the processing of locomotion-based environmental distance knowledge. Similarly, naturalistic research on subjective intra- and interurban distance is difficult to interpret because the relative influence of locomotion-based and symbolic-based distance knowledge is uncontrolled and unassessed (e.g., Säisä et al. 1986). It is also difficult in naturalistic settings to disentangle which characteristics of the environment provide distance information (pathway slope, aesthetic appeal, number of trees and curves, etc.). For these reasons, I focus on experimental research below.

1.2 Paper Overview

A complete model of environmental distance knowledge and estimation should provide answers to four questions:

a. What is perceived and stored during travel?
b. What is retrieved from long-term memory when distance knowledge is used (e.g., when distance is estimated)?
c. What inferential or computational processes, if any, are brought to bear on the information retrieved from long-term memory so as to produce usable distance knowledge?
d. How does the technique used to measure distance knowledge influence distance estimates?

In this paper, I focus on answers to questions a and b. Answers to question d are considered by Montello (1991). Question c and, to a lesser extent, question b are concerned with the psychological processes that describe how people acquire, store, and retrieve distance information (e.g., Thorndyke and Hayes-Roth 1982). The two topics, information sources and processes, are analytically separable to some extent because a given type of information may be stored and processed in alternative ways, and a given process may operate on any of several different types of information.

I adopt a framework here that posits multiple, partially redundant information sources differentially influencing knowledge of distances as a function of scale and availability. In other words, there is no single answer to the question of what source of information is the basis of distance knowledge. I organize these sources into three classes: (1) number of environmental features, (2) travel time, and (3) travel effort or expended energy. No models have been proposed in the literature that incorporate all of these sources. The plurality of possible sources that can explain a particular set of results is typically unrecognized. Existing research, therefore, often does not allow us to decide conclusively about the operation of a given source.

2 Number of Environmental Features

The most frequently discussed source of environmental distance information in the literature has been the number of features perceived during travel and/or recalled at the time of estimation. A feature would be any kind of object or element of structure in the environment perceptible during locomotion: turns, road signs, landmarks, intersections, barriers, and so on. Features are typically thought to be visually-perceived, though other modalities could presumably be involved.

2.1 Feature-Accumulation Hypothesis

The literature on distance contains several models or hypotheses linking features to subjective distance. The simplest version is that subjective distance will be determined by a rule that sets distance equivalent to the number of processed features encountered during locomotion along a given path. Analogous to the traditional "filled-duration" illusion (Buffardi 1971), this *feature-accumulation* hypothesis has been most extensively explored experimentally by Sadalla and his colleagues (e.g., Sadalla et al. 1979). Typically using pathways in a large laboratory room or hallway, these researchers have manipulated the number of right-angle turns, the number of intersections, and the memorability of words presented as part of a pathway. Their data indicate that increasing the number of pathway features encountered and recalled by subjects leads to increased distance estimates. The feature-accumulation hypothesis has been extensively tested with children, though not always supported, by Herman and his colleagues (e.g., Herman et al. 1986). Explicit counting of features (Downs and Stea 1977) such as blocks would be a variant of the feature-accumulation hypothesis.

2.2 Route-Segmentation Hypothesis

In addition to the accumulation hypothesis, a *route-segmentation* hypothesis has been proposed to explain the relationship between estimated distance and the number of features in the environment. This hypothesis suggests that traveled routes segmented by features will be subjectively longer than unsegmented routes. Allen and his colleagues have most fully elaborated and provided evidence for the segmentation hypothesis (e.g., Allen 1981; Allen and Kirasic 1985), using a methodology involving slide-simulated routes. These researchers have maintained that structural features of pathways induce them to be chunked or segmented into units or subdivisions, for the sake of cognitive economy. The units act like categories insofar as distances between units are exaggerated relative to distances within units. Thus, increased numbers of environmental features lead to increased distance estimates because of categorical exaggerations resulting from increased segmentation.

Virtually all studies on features can be interpreted in terms of the effect of segmentation on subjective distance. Work on hierarchies in spatial knowledge and estimated distance (e.g., Hirtle and Jonides 1985) can be interpreted in terms of spatial segmentation or categorization. The effects of "barriers" such as walls, examined in many studies, can also be attributed to route segmentation (e.g., Kosslyn et al. 1974; Newcombe and Liben 1982). However, researchers have noted that barriers not only segment routes, but they increase the number of features, influence visibility, and have implications for travel time and effort (discussed below).

2.3 Scaling Hypothesis

In addition to the accumulation and segmentation hypotheses, a *scaling* hypothesis has been proposed to explain the ostensible influence of pathway features on subjective distance (Sadalla and Magel 1980). This hypothesis requires that the psychophysical function for distance estimation be a power function with a positive exponent less than 1.0 (i.e. a positively decelerating power function). Such an exponent is usually found (e.g., Künnapas 1960). If so, the ratio of estimated to physical distance will be smaller for longer distances. A single estimate of an entire route would therefore be shorter than a sum of estimates of several segments making up the route, because longer segments are relatively underestimated as compared to shorter segments. Holyoak and Mah (1982) provide a model that may explain why such a decelerating function is found.

2.4 Evidence for Features

To summarize, environmental features such as turns or barriers have been shown to influence distance estimates. At least three hypotheses have been offered to explain this influence: the feature-accumulation, segmentation, and scaling hypotheses. No direct empirical comparisons between these hypotheses have been made. To a large extent, they have not been previously recognized in the literature as distinct alternatives. All three suggest that any characteristics of the environment or of the traveler that influence what features are perceived and stored during travel, or recalled when estimating distance, should affect the magnitude of distance estimates. The most obvious characteristic is simply the objective number of discriminable features in the environment. Also important is the relative distinctiveness or *salience* of features. More salient features will attract attention and tend to be remembered, and they appear to play important roles in structuring spatial knowledge in long-term memory (Couclelis et al. 1987; Sadalla et al. 1980). Organismic factors such as familiarity and travel purpose might affect subjective distance by altering the perception and/or retrieval of environmental features (e.g., Salmaso et al. 1983). Even the way a particular estimation technique activates stored knowledge into working memory should influence the magnitude of distance estimates (e.g., Holyoak and Mah 1982).

Affective factors, such as a traveler's mood or the evaluative qualities of places, might influence subjective distance via their influence on attention and memory for environmental features. The idea is intuitively plausible, and many proposals about the role of affective factors have been made (e.g., Smith 1984). Unfortunately, it is easy to make multiple claims about the direction of such an influence that are each reasonable yet mutually contradictory. Places with negative associations may be stored in memory as either closer or further away because of the importance of avoiding them; the direction the effect should take is not clear. Does one's optimism or pessimism play a role? There is much speculation about the importance of affective factors but very little empirical evidence for it.

More importantly, there are several null and even inconsistent findings about the effects of features in the literature (e.g., Heft 1988). Several characteristics of the research might help explain this. First, most of the positive findings have measured distance knowledge with psychophysical scaling techniques, while most of the negative findings have employed a reproduction technique. Differences between the two may contribute some important method variance to distance data (Klatzky et al. 1990; Montello 1991). Second, it may be misleading to describe all the diverse manipulations from different studies as examples of "features" -- a path turn and a toy landmark could obviously differ from each other in important ways. Perhaps features that do not induce some type of route segmentation will not have much influence on estimated distance. Finally, the most important explanation for discrepant results involves the assumption that an increase in pathway features will necessarily lead to an increase in estimated distance, rather than a decrease. In the next section on travel time, I will discuss reasons that this assumption may be untenable. Depending on such factors as attention and instructional set, increasing features might actually decrease estimates of traveled distance.

3 Travel Time

Travel time has frequently been proposed as a source of information for environmental distance. Golledge and Zannaras (1973) stated that "cognized distances increase with, and are directly related to the time required to traverse any given path" (p. 80; also see MacEachren 1980). This issue is not straightforward, however. It is undoubtedly true that travel time rather than distance is sometimes the relevant variable in models of spatial choice (e.g., Burnett 1978). And people often express separation between places in temporal terms. Clocks and watches are much more widely available than are instruments for measuring distance, and provide a relatively handy way to assess the extent of travel. Does this mean that people equate or confuse knowledge of travel time and distance? Or that their estimates of distance necessarily invoke temporal information? These questions are difficult to answer, in part because travel time and distance are usually highly correlated, given a particular mode of travel.

Similarly, actual and subjective distance are typically correlated strongly, as are actual and subjective time (e.g., Säisa et al. 1986). Because of these fairly strong and positive monotonic relationships, estimated time and estimated distance will be correlated even if there is no direct causal link between them.

3.1 Models and Evidence for Travel Time

The simplest causal model of the relationship between travel time and subjective distance would essentially equate subjective distance with subjective time. Ewing (1981) discredits this simple model by pointing out that large discrepancies between travel time and distance do not go unnoticed; no one thinks that 10 minutes in a traffic jam takes you as far as 10 minutes on an unclogged freeway. Knowledge of movement must be involved. A more sophisticated hypothesis, therefore, might posit a computational process that sets distance equal to travel time multiplied by travel speed, as in some models of "dead reckoning" navigation (e.g., Fujita et al. 1990). A different approach suggests that distance knowledge is not directly derived from temporal information but is subject to its influence because of certain heuristics people employ about the relationship of time and distance. These heuristics may have only a limited range of action, failing to operate when travel time and distance are quite discrepant. Cohen and Cooper (1962) described such an heuristic, the *tau-movement effect*. Evidence for the tau-movement effect is clearest when research subjects do not have much access to movement information, such as when riding blindfolded in an automobile at constant speed.

Many studies, including several cited above in the section on features, provide data on the general question of the relationship of travel time to distance knowledge for walked routes. The studies by Sadalla and colleagues examined the relationship of actual walking time to estimated distance. In four of their reported experiments, walking times did not differ between conditions that did result in large differences in estimated distance. Research by Herman and colleagues has similarly failed to find much empirical support for the idea that estimated distance is derived from travel time. A thorough study by Lederman et al. (1987) found no support for a tau-movement effect for walked routes.

Although counterintuitive to geographers, nearly all of the empirical evidence on the relationship of travel time to subjective distance is negative. However, by geographic standards, nearly all of these studies have been carried out with small pathways and trips of short temporal duration. It is plausible that travel time will influence subjective distance more strongly under conditions of large spatiotemporal scale. Furthermore, existing research has not adequately conceptualized or tested a model of travel time and subjective distance that incorporates subjective speed.

3.2 Insights from Time Psychology

Important insight into the possible role of travel time as a source of distance information can be gained by looking at the experimental literature on time psychology. Various "event" models have been offered for subjective time (Block and Reed 1978), much as feature models have been offered to account for subjective distance; perceiving an environmental feature can be construed as an event occurring during a travel episode. It has traditionally been thought that temporal intervals filled with events will seem longer than empty intervals (filled-duration illusion). This parallel between subjective time and distance suggests that their relationship might profitably be considered with respect to the role of events or environmental features encountered during travel. Despite this rather striking conceptual parallelism, however, the mostly negative findings reviewed above cast doubt on the relationship.

However, modern work in time psychology (e.g., Block 1992; Zakay et al. 1994) has gone far beyond the simple notion of a filled-duration illusion. Empirical evidence and theory now suggest that events occurring during temporal intervals may lengthen *or shorten* subjective time. Models proposed to explain this phenomenon have evolved around two ideas. The first is that subjective time is a function of attention to one of two internal processors, a temporal and a nontemporal processor (the former might be based on neural or metabolic events). The second idea is that people will use distinct strategies to estimate time depending on whether they are prompted to focus on time during the interval in question (whether they are prospectively or retrospectively instructed to estimate time, for instance). Thus, a drive through the state of Kansas may seem very long while you are doing it, because you are not distracted from attending to the temporal processor by events. If you think about the time of the drive weeks later, however, you will not recall many events and will thus remember the drive as being rather short.

So recent work in time psychology clearly suggests that if travel time did provide information for distance, increasing the number of features encountered during travel might actually decrease subjective distance. Such a decrease has never been predicted in the distance literature. In an unpublished dissertation, Montello (1988) unexpectedly found a significant decrease in subjective distance when subjects read and memorized a list of words while walking a laboratory pathway, as compared to a no-word control group. When estimated walking times were standardized with actual walking times, it turned out that subjects in the no-word condition, who had made longer distance estimates, relatively overestimated walking time the most. These data cast a definite wrinkle on the time-distance relationship. There are many details to be clarified about the nature of the temporal processors, the nature of intervening events, and the situations under which prospective or retrospective processes will actually operate[2]. But it is clear that modern ideas about time psychology should be refined and further examined for their relevance to distance psychology.

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[2]R. A. Block, personal communication, March 28, 1992.

4 Travel Effort

A third potential source of information for distance knowledge is the amount of effort or energy that a person expends while traveling through the environment. Given that people readily estimate distances in the absence of any significant energy output, such as when riding in an automobile, it is obvious that effort alone can not account for judgments of traveled distance. However, as with travel time, it is possible that judgments of distance derived primarily from other sources are subject to the influence of an effort heuristic. According to this heuristic, journeys that require more effort are probably longer in distance because longer journeys generally require more energy to travel.

Travel effort has been operationalized in several ways: the indirectness of routes and the presence of barriers (e.g., Newcombe and Liben 1982), hills or sloping pathways (e.g., Cohen et al. 1978), and even the need to carry weight or perform some other strenuous task while traveling (e.g., Bamford 1988). Evidence for the role of effort has primarily come from studies in which estimates of straight-line distance increase as the indirectness of routes increases (i.e., the straight-line distance from A to B is estimated to be longer when the route traveled from A to B is longer, because of turns or detours). Such an outcome has been attributed to an heuristic whereby straight-line distances are inferred from the spatial extent of movement (Lederman et al. 1987).

These findings are ambiguous in several key ways, however. As noted above, barriers not only increase route indirectness. They increase features and route segmentation, increase travel time, and decrease visibility. Some evidence indicates that transparent barriers do not affect estimated distance as do opaque barriers (e.g., Kosslyn et al. 1974), which suggests that effort is not the reason for barrier effects. Another ambiguity is analogous to a statistical "barrier effect". When people have to infer straight-line distances between mutually nonvisible places that are actually fairly close, random errors in distance knowledge are more likely to lengthen than shrink the represented straight-line distance between the places. Assuming topologically correct knowledge, there is simply less room for distance contractions than exaggerations between close places. Furthermore, if acute turns are distorted toward right angles (e.g., Sadalla and Montello 1989), the endpoints of a route containing acute turns would effectively be separated. Finally, there is evidence that people will tend to estimate route distances between places unless clear and explicit straight-line estimation instructions are given (Rieser et al. 1980).

There is thus little clear evidence for the role of effort or energy expenditure as a source of distance information. Effort might influence attentional mechanisms that operate on other sources of distance information. As is true for travel time, the influence of travel effort may require longer trips. Probably any manipulation that alters the normal mechanics of self-propelled locomotion such as walking will alter the proprioceptive perception of distance during that locomotion. There is fairly good evidence that the increased route distance caused by barriers, especially opaque barriers, is associated with increased estimates of straight-line distance, but no one has convincingly shown whether this is due to effort, time, visibility, the presence of features, angular distortions, or some other factor. Unfortunately, almost no research has been done that manipulates energy expenditure without confounding it with other variables, such as slope, locomotion mechanics, or route indirectness.

5 Summary and Conclusions

Knowledge of distance acquired via direct sensorimotor experience locomoting through environments may be based on one or more of three sources of information: number of environmental features, travel time, and travel effort. A review of the literature suggests that people take advantage of multiple, partially redundant information sources for acquiring and using knowledge of distances, an idea that many researchers have failed to recognize. Different sources may be used on different occasions or more than one source may be used in combination on a single occasion. Any single source will not provide a basis for distance knowledge in all situations.

The number of environmental features encountered while traveling has received the most empirical support as an important source of distance information. Models involving the processing of features enjoy the strong advantage of being able to accommodate the possible influences of many different organismic and environmental factors, particularly through attentional mechanisms: familiarity, travel purpose, affective states, and various physical characteristics of the environment. When visual access to the environment is available, and the traversed route is not too long, it is likely that perceived and remembered features will provide the major source of information for distance.

However there is an important need for replication of the results of feature research. This is especially true given the occasional negative findings and the possibility raised by recent work in time psychology that processing of features may decrease subjective distance under certain conditions. Furthermore, there is a need to refine our understanding of different types of features and the specific hypotheses that have been advanced to explain how they influence distance knowledge. At least three hypotheses (and some variants therein) have been proposed to explain processing involving features, including the accumulation, segmentation, and scaling hypotheses. The relevant properties of, and possible differences between, various types of path features should be further investigated (e.g., words vs. turns). More models of the mental activities of people moving through environments are needed: What goes on in the minds of people who are not given tasks to occupy their attention while they travel? Surely it is questionable to describe such situations as mindless "no-event" or "no-feature" control groups.

Subjective time could be similarly influenced by the organismic and environmental factors that might influence memory for features. Thus, subjective time is a good candidate either to mediate the effects of features on distance or at least to show parallel effects to those on distance. But in spite of the conceptual and intuitive plausibility of this idea, several studies that have investigated travel time as a source of distance knowledge have not produced much evidence for its importance. But the existing treatments of travel time have generally not considered the role of subjective travel speed. Also, the implications of a model of subjective time in which features or events encountered during locomotion in the environment can increase or decrease subjective time have not yet been addressed. Further analysis of the role of attention to various sources of knowledge during locomotion through the environment is clearly needed here as well. Travel effort or expended energy has likewise received very little empirical support as a source of distance knowledge, though again, definitive research has probably yet to be done.

So the empirical evidence available at this time points most strongly to the role of environmental features in distance knowledge. Research on opaque and transparent barriers suggests that features affect subjective distance primarily by segmenting routes. Either the segmentation or scaling hypotheses can explain this effect. Any features that break routes into distinct segments will tend to lengthen estimated environmental distances. Furthermore, structural features such as turns or opaque barriers that break pathways into separate vistas (Nasar et al. 1985) apparently have the most impact on subjective distance. This suggests that distance knowledge may typically result from a process of *summing vista distances*. According to this model, the subjective lengths of route segments that are visible from single vantage points (i.e., vistas) are summed to arrive at estimates for the entire route.

If visual access to the environment is not available (blindness, darkness, opaque obstructions, etc.), it is likely that heuristics involving travel time and/or effort will have their greatest influence on estimates of distance. Furthermore, nearly all experimental distance research has been carried out with fairly small-scale routes and short temporal durations. Some evidence indicates that various heuristic influences will be greater under conditions of large spatiotemporal scale (e.g., Hirtle and Mascolo 1991). Under these conditions, the ability to attend to and retrieve relatively continuous knowledge about vistas or elapsed movement is reduced. What's useful for estimating the length of a walk through a building is less useful for estimating the length of a day long train trip.

It is evident that research on the acquisition of environmental distance knowledge provides a rich opportunity for the interface of spatial and cognitive/behavioral sciences. The topic involves many issues ranging from low-level processes, such as the proprioceptive sensing of movement during locomotion, to higher-level processes, such as decision-making during trip planning. Research on the perception and cognition of distance is relevant to a wide array of models of human spatial behavior. This review makes plain, however, the great need for further conceptual refinement and the replication of phenomena that have been reported. As is often true, one of the greatest needs is for an understanding of the role of spatiotemporal scale. Unfortunately the difficulty of conducting well-controlled research, research supporting confident causal conclusions, increases dramatically with increased scale.

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