A Conceptual Model of the Cognitive Processing of Environmental Distance Information

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Abstract. I review theories and research on the cognitive processing of environmental distance information by humans, particularly that acquired via direct experience in the environment. The cognitive processes I consider for acquiring and thinking about environmental distance information include working-memory, nonmediated, hybrid, and simple-retrieval processes. Based on my review of the research literature, and additional considerations about the sources of distance information and the situations in which it is used, I propose an integrative conceptual model to explain the cognitive processing of distance information that takes account of the plurality of possible processes and information sources, and describes conditions under which particular processes and sources are likely to operate. The mechanism of *summing vista distances* is identified as widely important in situations with good visual access to the environment. Heuristics based on time, effort, or other information are likely to play their most important role when sensory access is restricted.

Keywords: Distance information, cognitive processing, spatial cognition.

1 Introduction

Entities and events on Earth are separated by space—this separation is distance. Human activity takes place over distance and involves information about distance. Distance information helps people orient themselves, locate places, and choose routes when traveling. It also helps people evaluate the relative costs of traveling from one place to another and utilize resources efficiently, including food, water, time, and money [1]. Understanding how humans think about and understand distance contributes to predictive and explanatory models of human behavior. For example, it has been axiomatic to geographers, planners, and transportation engineers that humans are effort minimizers and choose routes and destinations partially out of their desire to minimize *functional* distance [2], [3], [4]. Because overcoming the separation between places that are further away generally requires more time, effort, money, or other resources, we expect less interaction between places further away. This generalization has been considered so fundamental to explanation in geography that it has been dubbed the "First Law of Geography" (the repeated use of this phrase in

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textbooks and research literature suggests it is taken quite seriously, e.g., see the Forum [5] in the journal *Annals of the Association of American Geographers*).

Behavioral geographers and others proposed some time ago that is was not objective or actual distance that alone accounted for human activity. Instead, they proposed that models of human spatial activity could be improved by considering *subjective* distance—what people know or believe about distance [4], [6], [7], [8]. For example, when I choose to visit one store rather than another because it is closer, I base this choice on my *belief* that the one is closer, whatever the true distance is. Thus it is evident that understanding human perception and cognition of distances is necessary for understanding human spatial activity and interaction between places.

Although much navigation and spatial planning can occur without precise metric information about distances, or even without distance information at all, I have argued elsewhere that some quantitative information about distances is required to explain human behavior in the environment, for both conceptual and empirical reasons [1], [9]. Neither information about the sequences of landmarks nor information about travel times are sufficient by themselves (of course, travel time could provide the basis for metric information about the separations between places). Conceptually, some quantitative distance information was needed by our evolutionary ancestors in order to navigate creatively; such creativity includes making shortcuts and detours in an efficient manner. Inferring the direction straight back to home after several hours or days of circuitous travel requires distance information, not just information about landmark sequences or travel times. Such creativity clearly is still valuable in present times for many of us, in many situations. Empirically, systematic observation that people can make metrically accurate distance estimates, and can perform shortcut and detour tasks with some accuracy, supports the psychological reality of distance knowledge [1], [10], [11].

Recognizing its importance and pervasive role in human activity, this paper provides a comprehensive and interdisciplinary review of the cognitive processing of distance information by humans. It also proposes a conceptual model of the perception and cognition of environmental distance. As I stated in [1], a complete model of environmental distance knowledge and estimation provides answers to four questions:

1. What is perceived and stored during travel that provides a basis for distance knowledge?
2. What is retrieved from long-term memory (LTM) when distance information is used (e.g., when travel planning is carried out) that determines or influences distance knowledge?
3. What inferential or computational processes, if any, are applied to information retrieved from LTM to produce usable distance knowledge?
4. How does the technique used to measure distance knowledge influence estimates of distance?

Distance knowledge and its expression as measured data in cognitive research result from processes and information sources addressed by the first three questions, in addition to aspects specific to the measurement technique used to collect estimates, addressed by the fourth question. In [12], I reviewed techniques for measuring distance knowledge, comparing techniques based on psychophysical ratio, interval, and ordinal scaling; mapping; reproduction (i.e., retraveling); and route choice. Of course, researchers have uncovered significant new insights about distance estimation since my review. One of the most significant insights about estimating distance (and other spatial properties such as slope) concerns an apparent dissociation between spatial knowledge expressed via direct motoric action, such as retraveling a route as part of distance reproduction, and knowledge expressed via indirect, symbolic techniques, such as verbal estimation in familiar units (a common technique I grouped with ratio scaling methods in [12]), [13], [14].

In [1], I focused on the sources of information for distance knowledge, addressing primarily the first two questions above. To the extent that distance information is acquired via travel through the environment, knowledge of distances must ultimately be based on some kind of environmental information, such as the number of landmarks encountered, or proprioceptive information, such as the bodily sense of travel speed. I organized these sources of information into three classes: (1) number of environmental features, typically but not exclusively visually perceived, (2) travel time, and (3) travel effort or expended energy. I concluded that environmental features enjoys the most empirical support as a source of distance information, although not all types of features are equally likely to influence beliefs about distance. Features noticed by travelers and used by them to organize traveled routes into segments will most impact distance knowledge, e.g., [15], [16]. Two explicit variants of features as a source of distance information are *step counting* and *environmental pattern counting* (e.g., counting blocks).

Travel time is logically compelling as a source of distance information, especially in situations of restricted access to other kinds of information, but it has not been convincingly demonstrated in much research and is often misconceptualized insofar as researchers have failed to consider the role of movement speed. Also, travel effort enjoys very little empirical support but may still function when it provides the only possible basis for judging distances. Since 1997, new research has been reported on the perception of travel speed [17] and its role in distance cognition [18], [19]. Also, research has been reported on the role of effort that suggests it can influence the perception of vista distances when people anticipate they will need to climb a sloped pathway [20], [21]. Nonetheless, showing that experienced effort influences estimates of environmental distances that have actually been traveled remains an elusive phenomenon.

In this paper, I address the remaining question relevant to a complete model of directly experienced environmental distance knowledge and estimation, Question 3. This question asks what inferential or computational processes, if any, are brought to bear on information retrieved from LTM so as to produce usable distance information. To address this question, I describe alternative processes for how humans acquire, store, and retrieve directly experienced distance information. I summarize these processes in the form of a conceptual model that comprehensively presents alternative ways people process distance information and the conditions likely to lead to one alternative or another.

My review and model are organized around a theoretical framework that proposes there are alternative processes accounting for distance knowledge in different situations and multiple, partially redundant information sources that differentially provide information about distances as a function of availability and spatial scale. A few models of environmental distance processing have been proposed in the literature. The model I present below modifies and extends models proposed some time ago by

Briggs [22], Downs and Stea [23], and Thorndyke and Hayes-Roth [24]. These proposals contributed to a comprehensive theory of environmental distance information but have not been significantly updated in over two decades. Furthermore, these older models did not fully express the plurality of plausible distance processes, the idea that a single process can operate on different information sources, nor the idea that a single source might be processed in different ways. Thus, the evidence that researchers have put forth for some aspect of distance cognition is often consistent with multiple specific explanations, making its interpretation ambiguous. What's more, there are partially redundant cognitive systems for processing and estimating traveled distances. More than one system can operate within and between research studies, and even within individual people on different occasions.

2 Environmental Distance, Directly Experienced

As in my earlier review of sources of distance information [1], I am concerned in this manuscript with information about distances in *environmental* spaces [25]. These are physical spaces (typically Earth-surface spaces) that are much larger than the human body and surround it, requiring considerable locomotion for their direct, sensorimotor apprehension. Examples of environmental spaces include buildings, campuses, parks, and urban neighborhoods (it is largely an open research question as to how well spatially talented people can directly apprehend the spaces of large cities and beyond). Their direct apprehension is thus thought to require integrating information over significant time periods, on the order of minutes, hours, days, or more. However, unlike *gigantic* spaces (termed *geographic* spaces in [25]), environmental spaces are small enough to be apprehended through direct travel experience and do not require maps, even though maps may well facilitate their apprehension. Many studies, especially in geography, concern distance information acquired indirectly (symbolically) in naturalistic settings, at least in part, e.g., [26], [27], [28], [29], [30]. The results of theses studies are somewhat ambiguous with respect to how travel-based environmental distance information is processed.

There is a great deal of research on the perception of distance in *vista* spaces, visually perceptible from a single vantage point [31], [32], [33], [34], [35]. This research has often been concerned with evaluating the fit of Stevens's Power Law to vista distance estimates under various conditions. The Power Law states that subjective distance equals physical distance raised to some exponent and multiplied by a scaling constant. Most interest has been in the size of the exponent, which has usually been found to be near 1.0, a linear function (exponents < 1.0, a decelerating function, have been reported more often than exponents > 1.0, but both have been found). This work is relevant to our concern with environmental distance for at least two reasons. First, psychophysical distance scaling has been methodologically important in the study of environmental distance information, as I reviewed above. Second, I propose below that perceived distances in vista spaces provide an important source of information for environmental distance knowledge.

However, it is important to distinguish between "visual" and "spatial." Spatial information expresses properties like size, location, movement, and connectivity along one or more dimensions of space. Most visually-acquired information has a spatial aspect to it, but not all does—color provides perhaps the best example. And although vision provides extremely important spatial information to sighted people, especially spatial information about external reality distant from one's body, other sensory modalities also provide important information about space. These senses include audition, kinesthesis, and haptic and vestibular senses (some evidence even suggests olfaction may play a role for people [36]). There is apparently a spatial mode of cognitive processing that is more abstract than any sensory mode, and it is clear that spatial processing is not limited to or wholly dependent on visual processing [37], [38], [39], [40]. The fact that blind and blindfolded people can accurately estimate distances in the environment shows that vision is not required for the perception and cognition of distance, e.g., [41], [42]. The cognitive processes discussed below differ in their reliance on different sensory modalities, but it is apparent that different modalities provide partially redundant means of picking up distance information.

2.1 Active versus Passive Travel

Even restricting ourselves to distance information acquired directly during travel in the environment, we must consider whether this travel is *active* or *passive* [43], [44], [45], [46]. The terms actually reflect two relevant distinctions. More commonly made is the distinction between voluntarily controlling one's own course and speed versus being led along a given path by another agent—that is, making navigation decisions or not. Active travel in this sense could be called "self-guided." Driving an automobile is typically self-guided; riding as a passenger is not. The distinction is important because distance knowledge depends in part on one's attention to the environment, to one's own locomotion, or to the passage of time. Attention likely varies as a function of the volition of one's locomotory and wayfinding decisions.

A second, less commonly made, distinction is between travel that requires considerable energy output by the body versus travel that does not. Active travel in this sense could be called "self-powered." Walking and running are self-powered; driving an automobile and being carried are not. This distinction is important for distance cognition because of its implications for travel time, speed, and physical effort, all likely influences on distance knowledge. Furthermore, motor feedback resulting from self-powered travel provides input to a psychological system that updates one's location in the environment [47], [48]. These considerations cast doubt on the validity of using desktop virtual environments as environmental simulations in distance cognition research, e.g., [49]. Thus, the two distinctions between active and passive travel are relevant to distance knowledge because of their implications for the relative importance of different information sources and cognitive processes.

3 Cognitive Processes

I turn now to the question of how distance information acquired directly is cognitively processed during its acquisition, storage, and retrieval. In particular, how extensive and elaborate are the mental computations or inferences one must carry out in order to use information about environmental distance? I propose four different classes of processes that answer this question: working-memory, nonmediated, hybrid, and simple-retrieval processes. *Working-memory* processes are those in which relatively effortful (i.e., demanding on limited resources of conscious thought) inferential or computational processes are brought to bear on cognitive representations constructed in working memory (WM) when distance information is used; information about distance per se is not explicitly stored in memory during locomotion. *Nonmediated* processes are those in which distance information is encoded and stored directly during locomotion, without the need for much explicit inference or computation when distance information is used. *Hybrid* processes combine the two: Information about the distances of single segments is directly stored and retrieved, but effortful WM processes are required to combine the segments into knowledge of multi-segment distances. Finally, *simple retrieval* occurs when distance information is well learned and can be retrieved from long-term memory (LTM) as an explicit belief without any inferential processes. For example, one may have stored in LTM that it is about 240 miles from Fargo to Minneapolis, and can directly retrieve (i.e., recall or recognize) that without making an inference or computation. In some cases, a simple-retrieval process results from the explicit storage of distance information originally derived via other processes. Explicit estimates of distance would especially be available for simple retrieval when a person has previously made an explicit estimate based on other processes and then externalized it in words or numbers. In many other cases, it probably results in the first place from knowledge acquired indirectly via maps or language.

Models of spatial working-memory processes typically describe the WM representations as analogue or imagistic, although WM representations may be numeric, verbal, and so on. Two types of analogue representations may be considered. *Travel re-creation* refers to a process in which a temporally-ordered sequence of environmental images is generated that essentially re-creates a sequence of percepts experienced while moving through the environment. *Survey-map scanning* refers to a process in which a unitary, map-like spatial image is generated that represents part of an environment more abstractly, essentially from a vertical or oblique perspective. Foley and Cohen [50] refer to travel re-creation as *scenographic encoding* and survey-map scanning as *abstract encoding*. The distinction between travel re-creation and survey-map scanning is similar to the distinction by Thorndyke and Hayes-Roth [24] between environmental representations learned via navigation and those learned via maps. However, the distinction I make here refers to the nature of the representation and not to its manner of acquisition. Although the nature of one's learning experience almost certainly influences the nature of one's environmental representations (as Thorndyke and Hayes-Roth proposed and empirically supported), the extent to which this is true is still an open question (see review and discussion in [51]).

The generation and use of one or the other type of analogue representation might be empirically distinguishable in several ways. Thorndyke and Hayes-Roth [24] conjectured that patterns of performance on certain distance and angular estimation tasks would differ for the two. For instance, straight-line distance estimates should be less accurate than distance estimates along a route in the case of travel re-creation; the opposite should be true in the case of survey-map scanning. Siegel et al. [52] proposed that when a route is represented and accessed as a linear sequence (travel re-creation), distance estimates in opposite directions would differ in accuracy as a function of the direction in which the route was learned. Palij [53] suggested that what he called *imagined terrains* (re-created travels) should be readily accessible in any alignment that is necessary for the task at hand. *Cognitive maps* (Palij's term for survey maps) should require extra time and effort to access in alignments that differ from a canonical alignment, such as the alignment in which one has viewed the layout. Such alignment effects are robust and well established when involving in-situ navigation maps, e.g., [54], but somewhat inconsistent when involving mental representations acquired from direct experience, e.g., [55]. Either way, however, it is likely that a re-created travel would also be less accessible in non-canonical alignments, such as those not based on the forward direction of travel.

What types of effortful processes might be applied to the representations generated in working memory as part of WM (and hybrid) processes? Thorndyke and Hayes-Roth [24] provided detailed possibilities. In the case of information acquired via navigation (travel re-creation), they proposed that individual straight-line segments are estimated and summed in WM to arrive at an estimate of total route distance (they did not specify how individual segments are estimated). If straight-line estimates were required between points not in the same segment, angular estimation coupled with some "mental trigonometry" would also be required. In the case of information acquired via maps (survey-map scanning), straight-line distance between any two points is estimated from scanning the imaged map, as in image scanning [56]. If route distance is required, individual segments would have to be scanned and the resulting distances summed. Whatever the case, the existence of such WM processes is suggested by introspection, logical analysis of task demands, and scanning-time data, e.g., [57]. Furthermore, research shows that the context created when representations are constructed in WM during estimation can affect the magnitude of estimated distances considerably [58]. Among other things, it can lead to patterns of asymmetries wherein the distance from A to B is estimated to be different than the distance from B to A [59], [60].

Hirtle and Mascolo [61] suggested additional WM processes. They conducted a protocol analysis in which subjects thought aloud while estimating distances between US cities. Although such information would be strongly influenced by maps and other symbolic sources, their work richly suggests many possible processes that could be used to generate estimates from directly-acquired knowledge. Hirtle and Mascolo identified as many as 20 strategies or heuristics claimed to have been used by subjects, including simple retrieval, imagery, translation from retrieval of time, comparisons to other distances, and various forms of mathematical manipulation of segments (e.g., segment addition). They also found that the use of compound strategies (as in a hybrid process) was more likely with longer distances and less familiar places. That is, various indirect heuristics are more likely to be used when people do not have direct travel experience with a particular route.

For the most part, the WM processes described by Thorndyke and Hayes-Roth, and by Hirtle and Mascolo, do not explain what information is used to estimate the lengths of individual segments, nor how it is processed. But it is clear that processes used to access information with WM representations would be demanding of attentional resources—effortful and accessible to consciousness. With both WM and hybrid processes, however, repeated retrieval and inference with some particular distance information could eventually result in its processing by simple retrieval.

The class of nonmediated processes contrasts sharply with the WM and hybrid processes. Nonmediated processes do not rely on effortful inferences operating on WM representations. Instead, nonmediated processes lead to direct storage of distance information. Alternatively, information about time or effort might be acquired via a nonmediated process of some kind. Estimates of distance could then be derived from simple computational processes translating time or effort into distance.

Nonmediated processes essentially offer an alternative to the idea that the generation and manipulation of images in WM is necessary for generating environmental distance knowledge. In the general context of imagery and psychological processing, Gibson [62] wrote that:

> No image can be scrutinized...[a]n imaginary object can undergo an *imaginary* [italics in original] scrutiny...but you are not going to discover a new and surprising feature of the object this way. For it is the very features of the object that your perceptual system has already picked up that constitute your ability to visualize it. (p. 257)

This quote suggests that it would be necessary to “know” how far it is from A to B in order to construct an accurate image of it in WM—that “new” information cannot be extracted from images. If so, the imagery experienced and reported during distance estimation would be epiphenomenal. Pylyshyn [63], whose theoretical orientation otherwise differs radically from Gibson’s, offers a related criticism of the functional scanning of images based on a theory of tacit information.

Gibson did not specifically address environmental distance information. However, his framework does suggest one way that nonmediated processes might work to generate distance knowledge. The visual system is attuned to pick up dynamic changes in the *optic array,* called *optic flow,* that specify movement of oneself through the environment (*visual kinesthesis*). When coupled with perceptions of environmental layout, visual kinesthesis might lead to information about traveled distance without the necessity of constructing analogue memory representations. Rieser and his colleagues [48] developed this approach in their theory of *visual-proprioceptive coupling*. According to this, information about distance gained from optic flow is used to calibrate proprioceptive systems. These proprioceptive systems also produce distance information during locomotion, allowing acquisition of environmental distance information by blind or blindfolded subjects (also see [64]). An interesting way in which Rieser and his colleagues demonstrated calibration is to show that reproductions of walked distances can be altered by recalibrating the visual-proprioceptive coupling when research subjects are required to walk on treadmills pulled around on trailers.

Vestibular and kinesthetic sensing would likely play an important role in a nonmediated process for generating distance information [65], [66], although there are apparently situations where these proprioceptive body senses play a restricted role, such as when riding in an automobile [67]. The acceleration picked up by the vestibules and the semicircular canals is integrated over time by the central nervous system, again without the need for effortful scanning or manipulation of images. Information about traveled distance is thus available as a function of relatively automatic *perceptual updating* processes that have evolved to allow humans and other organisms to stay oriented in the environment without great demands on attentional resources [68], [69].

3.1 Processes: Summary and Discussion

I propose four classes of mechanisms by which humans process information about environmental distances: working-memory, nonmediated, hybrid, and simple-retrieval processes. These are primarily distinguished from one another on the basis of the extensiveness of the computations or inferences people carry out in WM in order to use distance information. According to a working-memory process, effortful manipulations are carried out on explicit representations constructed in WM. These representations are frequently analogue representations (i.e., images of path extensions) but need not be. Two major types of relevant analogue representations can be identified—travel recreation and survey-map scanning; I considered ways the two might be empirically distinguished. I also detailed several ways that WM representations could be manipulated in order to infer explicit estimates of distance (e.g., image scanning).

In stark contrast, a nonmediated process does not require the construction or manipulation of WM representations, analogue or otherwise. Instead, distance information is acquired and stored during locomotion as a result of implicit computational processes that are outside of the conscious awareness of the locomoting person. Hybrid processes combine WM and nonmediated processes. The lengths of single segments are stored and retrieved by a nonmediated process; information about the single segments is manipulated in WM in order to arrive at information about multi-segment distances. Finally, simple retrieval occurs when an explicit distance judgment can be retrieved from LTM without any inferential or computational processes. This would take place with directly experienced extents when an estimate of the length of some particular route has become well learned and stored explicitly in LTM.

Although only one of these processes can operate during a particular occasion in which distance information is used, it is not necessary to conclude that only one of them generally characterizes the processing of distance information. On the contrary, it is likely that all four processes are used in different situations. What determines which process operates? My review and description of the four classes suggests that one of the major factors involved is whether an explicit judgment of distance is required in a given situation, and whether that estimate is already stored as such in LTM. I turn now to a model that proposes some specific conditions that influence when such explicitness is likely to be necessary.

4 A Comprehensive Conceptual Model of the Cognitive Processing of Directly-Acquired Environmental Distance Information

Ideas about processes can be combined with ideas about sources of information in order to formulate a comprehensive conceptual model of the perception and cognition of environmental distance. I propose a model that addresses three questions posed in the introduction: (1) What is perceived and stored during travel that provides a basis for distance knowledge?, (2) what is retrieved from LTM when distance information is used?, and (3) what inferential or computational processes, if any, are brought to bear on the retrieved information so as to produce usable distance knowledge? (The model does not specifically address the influence of the techniques researchers use to

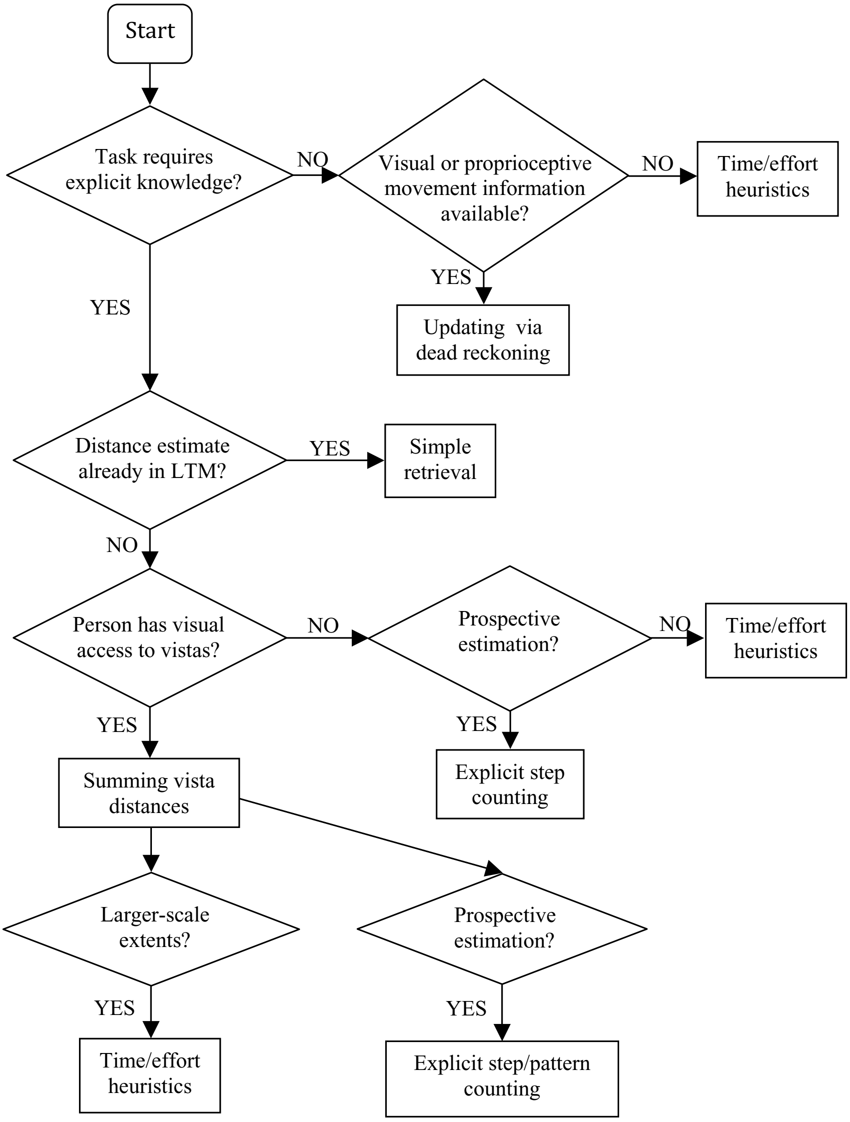

Fig. 1. Proposed model of the multiple processes and information sources for perceiving and cognizing environmental distance. Diamonds are decision nodes, rectangles are end states. All end states make knowledge of distance available in the form needed for the task being performed.

measure distance knowledge.) Figure 1 depicts the model. It is designed to accommodate the availability of alternative processes and multiple, partially redundant information sources. It does this by referring to the demands of the particular task, the availability of particular information sources, the degree of familiarity with the route in question, and its spatio-temporal scale.

At the outset, it is clear that information about environmental distance based on direct travel experience depends on the perception or awareness of body movement or change of position, whether valid or not. This perception generally derives from some combination of vision, kinesthesis, vestibular sensation, audition, and motor efference—any or all of them can contribute in a given situation. As a consequence, information that does not involve any sense or belief of movement, such as a judgment of elapsed time alone, cannot in itself account for distance knowledge.

The model first branches as a function of whether a task requires, or at least tends to activate, explicit knowledge of distance. Some tasks require only implicit information about distance. Locomotion over familiar routes in the environment is an important example; most of us find our way efficiently through the environment on a daily basis without thinking explicitly about our navigational decisions. Nonetheless, our coordinated and efficient travel still requires at least implicit distance knowledge in many situations. The fact that people sometimes have considerable implicit information about distances that guides their behavior in the environment does not, however, ensure that they will be able to externalize that information well using a distance estimation technique. It is therefore possible for subjects to estimate distances explicitly very poorly but do quite well actually navigating, e.g., [70].

In fact, locomotion along familiar routes sometimes does not require much distance information at all, as we observed above, although at least implicit knowledge of distance is often involved. A case in point: Some people can infer the straight-line direction from one place to another rather well, with less than 20° of error, even though they have never traveled directly between the two places [10]. This ability requiresdistance information of some kind. As long as the route is relatively small in scale, so that explicit information is not required, evidence is strong that people can perform this task using only the implicit information about distance provided by the optic flow and/or proprioceptive feedback occurring during locomotion, e.g., [71]. People may have little or no awareness of the operation of this process. As long as visual or proprioceptive information about movement is available, therefore, the model proposes that people (strictly speaking, their cognitive systems) will use a nonmediated process of perceptual updating to "reason" about distances and directions. However, if such perceptual movement information is not available (e.g., a subway ride at constant speed), then the model again suggests that people will need to rely on heuristics about the time and/or effort required to make the trip in order to arrive at knowledge of traveled distance. (As an aside, this situation suggests an important reason why people get lost much more easily when movement information is restricted: Without implicit spatial knowledge, their cognitive system must depend entirely on effortful explicit systems to maintain orientation, which becomes confused without ongoing attention.)

Other tasks require explicit information about distances, i.e., they require conscious awareness of distance quantities to various levels of precision. Notable examples are route planning and giving verbal route directions. In addition, I propose that travelers will require explicit distance information whenever they think about routes of large spatio-temporal scale, no matter what the task (e.g., even when navigating in familiar environments or performing path integration over long distances). Of course, an occasion requiring explicit distance knowledge that is of special interest to behavioral researchers is when a person participates as a research subject in studies of distance cognition. Nearly all such studies require subjects to make explicit (typically numerical, graphical, or verbal) estimates of distances in the environment.

If the task does call for explicit distance information, the model next asks whether an estimate of the length of a given route is already stored in LTM. If it is, the process of simple retrieval operates. This might be the case when a person is very familiar with a particular route and has reasoned about its length in the past.

The model then asks whether the traveler has visual access to vistas; that is, can the person see (rarely, hear) the extents of vistas that end at walls or other visual barriers in the environment? Vistas would be inaccessible to people with severe visual impairment, to people wearing blindfolds, or to people in darkness. If a person does not have access to vistas, then the model asks whether the acquisition of information used to estimate distance occurs under prospective conditions. Prospective conditions exist when a person knows in advance of traveling through the environment that an estimate of distance will be requested. In such cases, step or pattern counting can be used as a way to estimate distance. If prospective conditions do not hold, the person would need to use heuristics about the time and/or effort required to make the trip in order to explicitly estimate distance, after travel is complete. In such cases, subjective distance and time (or effort) will be most strongly related.

If visual access to vistas is available, the model proposes that visually-perceived and retrieved environmental structure will provide the major source of information for distance. Under these conditions, distance knowledge is derived from a hybrid process in which the perceived lengths of route segments that are visible from single vantage points (i.e., vistas) are summed to arrive at estimates for the entire route. This can be termed *summing vista distances*. Any structural features that induce segmentation of routes into vistas, such as opaque barriers, thus tend to elongate estimated environmental distances under the appropriate conditions.

A variety of theoretical and empirical claims motivate my stress on the importance of vista spaces in distance cognition. Gibson [62] emphasized the perception of vistas as integral to the perception of environmental structure under ecologically realistic conditions. A great deal of research on the influence of environmental features (reviewed in [1]), including research on opaque and transparent barriers, points to the import role of discrete pieces of the environment that are visually accessible from particular viewpoints. This stress on vistas also echoes more general theories of human and robotic spatial learning and orientation that posit their central function, [72], [73].

When visual access to vistas is available, and explicit distance information is required, I propose that summing vista distances is the primary mechanism for arriving at distance estimates. In addition, if a prospective estimation situation exists, people can use either step counting or environmental pattern counting if they are aware of such strategies and are not otherwise distracted from using them. The possible moderating influence of various heuristics is also allowed here by the model. These heuristics could be based on travel time or effort, or on such things as route indirectness or the number of features that do not obstruct visibility. The model hypothesizes, however, that heuristic influences will most likely operate with routes of large spatio-temporal scale (i.e., long routes). Under such conditions, the ability to attend to and retrieve relatively continuous information 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 long train trip. For instance, [61] noted that indirect strategies such as time retrieval were more commonly reported with longer distances. Similarly, [74] found an effect of travel effort on estimated distance only for walks that were at least several minutes in duration (as opposed to walks of 45 to 90 seconds).

5 Summary and Conclusions: Future Research Directions

In this paper, I proposed that people process information about environmental distances via one or more of four classes of processes operating on one or more of three sources of information, information acquired during travel through the environment. The four processes include working-memory, nonmediated, hybrid, and simple-retrieval processes. The three sources of information include number of environmental features, travel time, and travel effort. Previous reviews have failed to recognize the plurality of processes and sources that could account for distance knowledge. A comprehensive review of the literature suggests that at different times, people take advantage of alternative processes and multiple, partially redundant sources for acquiring and using information about distances in the environment. The conceptual model presented in Figure 1 attempts to show the conditions that determine which of these multiple processes and information sources will actually operate in a given situation.

It is evident that the perception and cognition of environmental distance is a fruitful research topic for the integration of many aspects of spatial cognition research. The topic involves issues ranging from low-level processes, such as the proprioception of one's movement speed during locomotion, to higher-level processes, such as the representation and manipulation of information via mental imagery. Such research has the potential to help address many interesting theoretical and practical questions related to human behavior in the environment. This review suggests, however, the need for further conceptual refinement and the empirical replication of phenomena that have been previously reported. In particular, we need to understand better the way environmental features of different types will or will not structure mental representations of environments, and the situations in which time and distance heuristics operate. Although I based my proposal that the summing of vista distances is a prominent mechanism for the cognitive processing of environmental distance information, this proposal needs further direct empirical evaluation. Finally, research should address the question of how distance information acquired in various ways, both directly and indirectly (symbolically), is combined or reconciled.

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