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Chapter 11

A New Framework for Understanding the Acquisition of Spatial Knowledge in Large-Scale Environments

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People acquire knowledge about the spatial layout of the places they experience (cities, neighborhoods, buildings). This includes knowledge of locations, distances, and directions. The acquisition of this knowledge begins immediately, as soon as one arrives in a place, but presumably continues over long time periods, for months, years, and even decades. This knowledge can become quite extensive and elaborate. It provides a framework for the organization of experience and supports sophisticated spatial behavior such as creative wayfinding and direction giving. The developmental process of acquiring knowledge about the spatial layout of places over time is termed.

Theoreticians from a variety of disciplines (cognitive, developmental, and environmental psychology; behavioral geography; planning and architecture; computer science) have attempted to describe and model spatial microgenesis. The long-dominant framework for understanding this process posits the following sequence: knowledge is initially acquired, followed by knowledge, which is followed by knowledge. In brief, according to this, landmark knowledge is knowledge of distinctive objects or scenes stored in memory. Route knowledge is knowledge of travel paths connecting landmarks. Survey knowledge is configurational knowledge of the locations and extents of features in some part of the environment that is not limited to particular travel paths. In this chapter I will reconsider the dominant framework in some detail, identify some problems with it, and offer an alternative framework that I believe is more conceptually coherent and more consistent with research evidence.

The Dominant Framework

The most influential expositions of the dominant framework are by Hart and Moore (1973; Moore, 1974) and, especially with respect to microgenesis, Siegel and White (1975). Many of their ideas came from Piaget's extensive theorizing about spatial ontogeny, including his idea of a progression from topological to projective and metric knowledge (e.g., Piaget and Inhelder, 1967). Other important influences were tinct types and stages of spatial knowledge. This last point echoed earlier proposals by Tolman (1948) in his distinction between "narrow strip maps" and "broad comprehensive maps," and later by Appleyard (1970) and Rand (1969) in their characterizations of sketch maps as being "sequentially dominant (route maps)" or "spatially dominant (survey maps)." Finally, Lynch's (1960) identification of the features of urban images (landmarks, paths, edges, nodes, districts) has also been important to the development of spatial microgenesis theory.

One comment is in order before describing the dominant framework further. There is a long tradition of reasoning by analogy across different domains of development (e.g., G. Stanley Hall's doctrine at the turn of the century). Werner's (1948) is an explicit example of this. According to this principle, increasing structural differentiation and hierarchical integration represents a general developmental principle, a principle about systematic processes of change over time. Among other types of development, the principle was proposed to apply to both knowledge changes with increasing familiarity (microgenesis) and knowledge changes across the lifespan (ontogenesis). Of course, not everyone has accepted the legitimacy of this strategy of developmental reasoning by analogy. I believe, as many people do, that the strategy is sometimes a useful heuristic but should not be taken too literally. With respect to the present discussion, I do not believe that microgenetic changes in spatial knowledge need be particularly similar to ontogenetic changes. So even though much of the inspiration for the dominant microgenetic framework comes from ontogenetic theorizing, I will focus on microgenetic research with adults in my discussion below of a new framework. I leave open the question of the new framework's relevance to ontogenesis (however, see Mandler, 1988, for an ontogenetic framework that shares much with my new framework for microgenesis).

I turn now to a more detailed examination of the elements of the dominant framework. According to the dominant framework, landmarks are discrete objects or scenes (patterns of objects against a background) that are stored in memory and recognized when perceived. "Landmarks are unique configurations of perceptual events (patterns)" (Siegel and White, 1975, p. 23). Some conceptualizations posit special cases of landmarks (e.g., reference points, anchor points) that serve important roles in the organization of spatial knowledge (see Presson and Montello, 1988, for a detailed discussion of the meanings of "landmark"). Most critically for the present discussion, landmarks are discrete units that do not in themselves contain spatial information, other than the local spatial information implied by recognizable pattern. Landmark knowledge is acquired first, according to the dominant framework.

The second element of the dominant framework is route knowledge. Routes are typically described as sequences or "chains" of landmarks linked by experienced paths of movement connecting them. Route knowledge consists of information about the order of landmarks and minimal information about the appropriate action to perform at "choice-point" landmarks, such as "turn right" or "continue forward." Importantly, such knowledge is typically described as not containing information about metric distances and directions, at least not during initial acquisition.

> Routes are nonstereotypic sensorimotor routines for which one has expectations about landmarks and other decision points. If one knows at the beginning of a "journey" that one is going to see a particular landmark (or an ordered sequence of landmarks), one *has* [italics in original] a route... [A] memorized route would be ... more akin to paired-associate learning, changes in bearing associated with arrival at "stimulus" landmarks... Learning between landmarks is, to some extent, incidental and irrelevant except to the extent that intermediary landmarks serve as course-maintaining devices... A conservative route learning system would then be, in effect, "empty" between landmarks.... [T]he "empty" space between landmarks receives "scaling" during extended experience with the routes. (Siegel and White, 1975, pp. 24–29)

Survey knowledge, the third element of the dominant framework, is said to derive from accumulated route knowledge. It is a map-like, or at least configurational, representation of metric spatial relationships between non-linearly-aligned sets of environmental features such as routes and landmarks (and broader elements such as districts), organized within a common frame of reference.

> Once routes with termini become interrelated into a networklike assembly, the gaps are gradually filled in ... The landmark-connected-by-routes spatial representation becomes more gestalt-like ... These "configurations" enhance way-finding, and they may be a necessary condition for inventions of new routes ... there are varying degrees of integration or gestaltness of the spatial representation. (Siegel and White, 1975, pp. 24–30)

Survey representations can encode broad areal patterns. They develop when knowledge of separate routes is *integrated* or combined into more complex clusters or networks of routes. Survey knowledge includes "direct" relational information about features between which one has never directly traveled. Evidence for its existence, therefore, consists of the ability to take shortcuts, create efficient routes, and point directly between landmarks (Siegel and White, 1975; Hardwick et al., 1976; Landau et al., 1984). All of these tasks require knowledge of both metric distance and metric direction in order to perform accurately.

Simulations and computational models of wayfinding and environmental learning have typically made distinctions similar to the dominant framework between different types of spatial knowledge. Golledge et al., (1985) describe a simulation of spatial learning consisting of a linear structure of links connecting ordered choice points, this route knowledge being stored "mainly in the form of procedural knowledge." Kuipers and Levitt (1988) review several of their computational models of wayfinding in which spatial knowledge is said to exist in a hierarchy of multiple forms, including distinct procedural, topological, and metrical structures. Their scheme reflects the dominant framework: "[A]ssimilation of the cognitive map proceeds from the lowest level of the spatial semantic hierarchy to the highest" (p. 26; see also, McDermott and Davis, 1984).

There has been some debate about the relative primacy of landmarks versus routes (see Evans, 1980; Golledge, 1987), but very little about the essential character of the elements of the model or the idea of a qualitative microgenetic trend. Numerous authors have echoed the dominant framework with only minor variations as a model of spatial microgenesis (Chase and Chi, 1981 [they describe it however, as "undoubtedly an oversimplification"]; Clayton and Woodyard, 1981 Thorndyke and Hayes-Roth, 1982; Lloyd, 1989; Hirtle and Hudson, 1991). Notably, Evans (1980) suggested that:

> [w]hether these ... trends reflect qualitative shifts in spatial cognition or quantitative, scalar changes is a point of controversy. Several studies suggest that memory for exact object location in the environment improves with experience but that the relative position of objects in space is accurately comprehended with little experience. (p. 275)

However, this observation has not, to this point, resulted in any substantial modification to the dominant framework (as suggested by the many recent works in the list of citation).

In sum, the dominant existing framework for understanding spatial microgenesis posits a qualitative transition sequence between three distinct types of spatial knowledge: landmarks, routes, and survey knowledge. It is generally agreed that some people with a great deal of experience in a place may have configurational knowledge of the relations between features [though some (e.g., Moeser, 1988) have questioned whether metric survey knowledge develops at all]. Others with less experience may have only nonrelational knowledge of landmarks or knowledge of linked sequences of landmarks. All versions of the dominant framework generally imply (with varying degrees of explicitness) that people encode and store only circumscribed features and topological relations during early stages of learning. There ostensibly exist periods during environmental learning in which no metric information about distances and relative directions is stored.

A New Framework

For the remainder of the chapter, I present a new framework for understanding spatial microgenesis by adults in environmental spaces. After a concise presentation of this framework, I discuss each of its components in more detail and provide substantiating rationale and evidence. The framework consists of five major tenets:

1. There is no stage at which only pure landmark or route knowledge exists, knowledge that contains no metric information about distance and direction (relative locations of places). Metric configurational knowledge begins to be acquired on first exposure to a novel place.
2. As familiarity and exposure to places increases, there is a relatively continuous increase in the quantity, accuracy, and completeness of spatial knowledge (quantitative rather than qualitative shift). Although this knowledge may become fairly accurate and extensive rather quickly, increases may continue indefinitely with further experience.
3. The integration of knowledge about *separately learned places* (experienced as part of unitary travel episodes) into more complex, hierarchically organized knowledge structures represents a significant and relatively sophisticated step in the microgenesis of spatial knowledge. This is the only relatively qualitative change process during microgenesis.
4. Individuals with equal levels of exposure to a place will differ in the extent and accuracy of their spatial knowledge. Such individual differences are likely to be especially profound with respect to the degree of knowledge integration.
5. Linguistic systems for storing and communicating spatial knowledge provide for the existence of relatively pure topological knowledge, or at least non-metric knowledge. However, such non-metric knowledge exists *in addition to* metric spatial knowledge, not as a necessary precursor or intrinsic part of it.

The first tenet states that there is no stage or period during spatial microgenesis in which acquired knowledge consists solely of qualitatively distinct forms of non-metric knowledge such as landmarks or routes. To begin with, there are conceptual difficulties with the suggestion that exclusively non-metric stages of knowledge exist. The existence of exclusively non-metric cognitive space is a little difficult to reconcile with the fact that perceptual space is clearly metric. And while it is true that navigation can often be successfully completed given only a string of landmarks and minimal turn instructions, it is sometimes not the case. The ability to make shortcuts, fend with detours, and perform path planning based on metric comparisons (distance, time, effort) would have been very adaptive to our hunter–gatherer ancestors; in fact, to many non-human species (Gallistel, 1990, reviews evidence for the metric layout knowledge of non-humans). Such skills may be less important in our highly regularized and well-labeled (sometimes) built environments, but they are certainly not obsolete.

The dominant framework's proposal that only non-metric knowledge exists during periods of early learning implies that people should be unable to accurately answer questions about metric distances and angles between locations to which they have been minimally exposed. They should not have knowledge of metric spatial "configuration" and should be unable to estimate "straight-line" spatial relations of locations between which they have not directly traveled. Much research clearly shows this is not the case. Decades ago, Worchel (1951) demonstrated that blind subjects could successfully complete a "triangulation" task that required them to walk straight back to a starting destination after traversing angled pathways one time. Of course, performance was not without error, but it was much better than chance and than non-metric knowledge alone would support. But here is the critical point: performance varied across topologically equivalent pathways that varied in metric properties (i.e., varying segment lengths meeting at varying turn angles) in ways that corresponded to the metric manipulations. Since then, many other investigators have replicated these findings (Hardwick et al., 1976; Kozlowski and Bryant, 1977; Levine et al., 1981; Lindberg and Gärling, 1981; Smyth and Kennedy, 1982; Foley and Cohen, 1984; Lederman et al., 1987; Holding and Holding, 1989; Sadalla and Montello, 1989; Klatzky et al., 1990; Montello and Pick, 1993). These studies have reported data indicating a significant ability of subjects with minimal exposure to pathways to walk straight-line shortcut paths or indicate shortcut directions by pointing, sometimes termed *path inte-*

gration or *path completion*. And when topologically identical pathways varying in metric properties are compared, these studies indicate that subjects' responses are sensitive to the metric variations. That is, subjects respond differently when turning 10° than when turning 40°, and they respond differently when walking 3 and 6 m pathway segments than when walking 3 and 4 m segments.

Three additional points must be clarified about the first tenet. First, I am not claiming that metric knowledge (or any environmental knowledge) is necessarily acquired *automatically*. Although I believe that *updating* of location during locomotion is to some extent automatic, it is likely that people do not acquire much metric knowledge without paying attention to the environment and/or to their movement. Little or no knowledge may be gained if one is very distracted during travel. A second point is that early metric knowledge of layout may in fact be very narrow and "strip-like." But a metric knowledge structure that encodes only a thin strip of the world to which one has been exposed is quite different than a non-metric string of landmarks. Finally, I do not wish to suggest that discrete environmental features such as landmarks play no role in the organization and use of spatial knowledge; on the contrary, I believe they are important in this way. The first tenet does suggest, however, that directly acquired spatial knowledge never consists solely of discrete and aspatial landmarks.

The second tenet follows naturally from the first: with additional locomotor and perceptual experience in a place, familiarity with the layout of the place increases, resulting in more extensive, complete, and accurate knowledge of that place. Familiarity breeds precision also, insofar as people become more certain of their knowledge and metric representation becomes less fuzzy (see discussion of qualitative metrics below). Given that knowledge acquisition includes metric layout properties from the start, the changes in knowledge over time are relatively continuous and quantitative in nature. They are not well described as consisting of qualitatively distinct stages or knowledge structures.

There is a discussion in the literature about the speed with which sophisticated and extensive spatial knowledge develops (summarized in Evans, 1980; Golledge, 1987). Some authors have produced evidence that a great deal of metric knowledge of towns or campuses is acquired in as little as a few months. But spatial knowledge of large and complex environments is never an exact copy of those environments; the fact that there will always be terra incognita just outside of one's known environment suggests that the amount and accuracy of knowledge can increase indefinitely with years and even decades of experience. Unfortunately, there is very little research specifically focused on very long-term spatial knowledge and no controlled longitudinal studies spanning long time periods (i.e., decades).

The new framework's third tenet largely agrees with the dominant framework. A qualitative shift in knowledge results from the integration of knowledge about separately learned places (not to be confused with the within-path integration or path completion discussed earlier). In essence, spatial knowledge about a place experienced during a unitary travel episode is stored together in memory. These separate knowledge units may be quite uncoordinated with each other, resulting in apparent metric inconsistencies (Montello, 1992); a person may be quite unaware of the relationships between separated places. [The separate units or chunks may themselves contain metric knowledge that is distorted as a result of categorical distortion effects (e.g., McNamara, 1986)]. Through additional experience (direct, maps, or communications with others), people come to understand the relationship of the separate places and integrate the units into more complex knowledge structures within some common frame of reference (Hanley and Levine, 1983; Golledge et al., 1991, 1993; Montello and Pick, 1993). The (partially) hierarchical structure of environmental knowledge arises at this point (McNamara et al., 1989). In part, because of the heavy load that integration places on processing capacity, it is qualitatively more difficult than general spatial knowledge acquisition (e.g., Golledge et al., 1993). But like general acquisition, integration is expected to continue indefinitely with additional experience.

Of course, individuals will differ in the extent and accuracy of their spatial knowledge. Some of this is simply due to differing amounts of exposure to a place (and different types of exposure). But individuals will also differ in both fundamental abilities for acquiring spatial knowledge (intellectual abilities) and in acquired strategies for encoding and decoding spatial knowledge (which should be amenable to training). Because of its qualitative difficulty, individuals are expected to differ especially profoundly with respect to their ability to integrate knowledge.

Finally, as expressed in the fifth tenet, the new framework does allow for the storage of non-metric spatial knowledge in a linguistic format, or in whatever non-spatial format underlies linguistic knowledge (i.e., deep-structure propositions). Examples include pure topological relations, such as "connecting" and "surrounding," as well as non-metric relations that are, strictly speaking, more than topological such as "proximate to" and "to the right of." An especially important example is an ordered sequence. Such relations are sometimes stored in a non-spatial format separately from metric spatial knowledge; alternatively, they are not directly stored at all but "extracted" from metric knowledge representations like they could be from a map or from the world. In other words, purely non-metric forms of spatial knowledge do not by themselves constitute the totality of one's spatial representations of the environment, nor are they a necessary precursor to metric knowledge, as suggested by the dominant framework. Evans (1980) expounded essentially this idea: "The view adopted here is that knowledge about the content and location of places in the geographic environment is stored in both propositional and analogical form" (p. 261).

Thus, research on linguistic spatial terms (Mark and Frank, 1991; Landau and Jackendoff, 1993) and on topological knowledge (Egenhofer and Al-Taha, 1992) should properly be interpreted with respect to a subset of spatial knowledge structures, not with respect to spatial knowledge in general. In many cases, non-metric knowledge will be derived from metric representations (giving directions that are not previously well practiced). In others, metric representations will be constructed from non-metric input (constructing "mental models" to understand text). I do not mean to imply by this tenet, however, that language is incapable of expressing metric spatial relations, only that it is well suited to expressing non-metric relations and often does.

The conclusion that there exist two or more distinct subsystems that represent spatial information in different formats is consistent with much theorizing on spatial representation (though there is a clear need for more empirical evidence of this idea). One of the earliest and most complete proposals of this kind was offered by Kuipers (1982). He suggested that spatial knowledge is stored in multiple disconnected components, and includes separate metric and topological components (somewhat different than the dominant-framework style model presented by Kuipers and Levitt, 1988, discussed above). Kosslyn (1987) proposed that the two hemispheres of the brain are differentially specialized for processing categorical (left) or coordinate (right) spatial representations (see Rybash and Hoyer, 1992, for an appraisal of this idea). McNamara et al. (1992) hypothesized that spatial knowledge is stored in at least three separate formats: temporal strings, propositions, and metric spatial representations.

Conclusions

I have argued that the process of acquiring spatial knowledge in large-scale environments is primarily one of quantitative accumulation and refinement of metric knowledge rather than qualitative shifts from non-metric to metric forms of knowledge. The integration of knowledge about separately learned places takes its place as a key concept in knowledge development. The framework I propose represents a shift in our understanding of changes in spatial knowledge over time, a shift that better accommodates empirical findings on environmental learning and more coherently fits with other theories of learning, cognition, and behavior.

Consideration of the new framework directly suggests important research questions to be addressed in the study of spatial knowledge changes over time. Mechanisms and processes by which spatial knowledge becomes integrated is surely one of the central research questions. To what extent are adults able to integrate knowledge of separate places? Does knowledge integration require certain types and amounts of travel experience, or will it occur "spontaneously" with the passage of time and thought?

Another critical need is for a more refined model of the form of environmental spatial knowledge. The framework I have presented proposes that adults develop metric knowledge of environmental layout. However, even in mature forms the knowledge is not particularly cartographic-like, insofar as it is typically imprecise, incomplete, fragmented, and inaccurate to some considerable degree (not to imply the complete absence of such limitations in cartographic maps). In other words, a complete and uniform Euclidean space of high resolution is clearly an inadequate model of environmental knowledge (a point many writers have made). One promising approach to this issue is the application of a qualitative metric to environmental spatial knowledge (e.g., Frank, 1991; Freksa, 1992; Montello, 1994). Such an approach models spatial or temporal knowledge as consisting of a relatively small set of coarse or "fuzzy" categories of quantities. While I maintained above that the empirical evidence of subject performance at

path completion tasks requires metric knowledge for its explanation, it does not require terrifically precise metric knowledge.

A related issue is the question of the role cartographic maps play in spatial knowledge acquisition. Maps are the most efficient and effective way of communicating metric properties of larger scale places, especially configurations (layout shapes). Although not consistent with the new framework proposed here, some have maintained that survey knowledge hardly develops much from direct experience alone but requires exposure to maps (Thorndyke et al., 1982; Moeser, 1988). How precise, accurate, and complete does layout knowledge of a place become in the average adult without exposure to maps of that place? How precise, accurate, and complete can it become? Do people combine knowledge of layout derived from maps and direct experience, and if so, how?

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