Human spatial memory : remembering where
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Proximity and Precision in Spatial Memory

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Almost 50 years ago, George Miller's (1956) survey of the literature on human information-processing capacity resulted in his being persecuted by an integer, specifically the number 7, which at that time had magical properties (see Miller, 1956). Today, our consideration of the literature on human spatial memory has led to similar vexation. We too have been visited repeatedly by an integer, in our case the number 2. Miller's troublesome number came in a variety of disguises, but none of these was so opaque as to make the intrepid integer unrecognizable. Similarly, we see significant diversity in the context of spatial cognition, but dual systems or processes are a consistent theme. Repeatedly, we have encountered accounts of two means of coding spatial relations, one related to precision and one to proximity. Rather than ignore this intriguing phenomenon, we elected to address this dauntless digit directly in this chapter.

Our approach is straightforward. First, we describe select dual-processing accounts that make clear distinctions and hence hold theoretical promise. These descriptions conclude with consideration of types of evidence that are used to differentiate between systems or types of processing. Second, we present some experimental findings that muddy the conceptual waters a bit by showing what happens when two different dual-processing accounts are examined in the context of a single procedure. Third, we tread well beyond evidence from these studies to present some musings that might serve to link current efforts to past approaches and to stimulate future research on how people remember "where."

Before proceeding further, we engage in the courtesy of providing general definitions for our terms. For our purposes, *memory* is simply a record of experience, the existence of which is inferred from a change in capability, behavioral or cognitive, afforded by that experience. Accordingly, *spatial memory* is basically a record of geometric relations involving observers, objects, and surfaces. The term *system* in this context connotes a distinct assemblage of components and accompanying principles dedicated to a particular function. Dual-system accounts of spatial memory, then, involve a distinction between different components and principles dedicated to providing the observer with information about spatial relations after encounters with objects, surfaces, and events. Concomitant with the idea of distinct spatial memory systems is the assumption that, although a record of spatial experience is formed, each system's components and principles regularly delimit and perhaps modify the information to which it is dedicated This selectivity and assimilation are referred to as *coding*. Thus, to hypothesize that spatial memory systems involve different means of coding information is to predict different consequences from the same spatial experience. Used in this manner, coding is a type of process, that is, another way of referring to system components and principles doing their job. Thus, when the term *processing* is used in this discussion, it is a synonym for coding.

DUAL CODING ACCOUNTS OF SPATIAL MEMORY

One of the intriguing aspects of dual coding treatments of spatial memory is that although none of the accounts corresponds directly to another, there is enough conceptual similarity among them to motivate efforts to integrate them into a common framework. In the descriptions that follow, we emphasize components of various dual coding accounts that yield both proximity and precision in memory for spatial location. From the outset, we acknowledge that these accounts are principally, if not exclusively, concerned with spatial information acquired through vision. This fact may facilitate efforts to integrate them into a common framework, but simultaneously it may limit the generalizability of conclusions regarding spatial memory.

Perception-Action Versus Cognitive Systems

This dual-system account contrasts the rapid, unconscious processing of spatial location to support immediate action with slower, conscious processing that creates an enduring record of spatial experience. Through conceptual analysis and a series of informative and straightforward experimental studies, Proffitt and his colleagues (Creem & Proffitt, 1998, 2001a, 2001b; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Wraga, Creem, & Proffitt, 2000) developed a well-articulated version of this theory. Although this distinction is supported by evidence from a variety of experiments, its foundation was laid out in a series of studies involving perception of and memory for geographic incline.

It is widely understood that observers in situ typically overestimate the slant of hills. Yet, the stepping behavior of hill climbers does not reliably suggest such inaccuracy. This contrast was demonstrated simply and elegantly in a series of studies by Creem and Proffitt (1998) in which observers indicated perceived or remembered incline by either estimating it verbally or matching it motorically using a manual response board. Participants significantly overestimated the incline of hills with verbal judgments, but motor estimates were highly accurate. When they relied on memory for the incline, even with a brief delay, observers' verbal overestimates reliably increased. In contrast, their motor estimates were not affected by very brief delays. However, these responses were context sensitive. Given a delay of 1 day or when taken to a different location, error in participants' motor responses began to resemble those in their verbal responses.

Creem and Proffitt (1998, 2001a) interpreted their findings as support for two different systems for processing spatial information. With minimal delay and no change in an observer's position, motor responses are the product of a perception-action system, which provides spatial information relevant for visually guided action implicitly, that is, without the observer's awareness or conscious intent. This system enables an observer to perform known actions (such as stepping or reaching) immediately within the environment, updating changes in observer–environment relations such as viewer relative location, orientation, and movement. Because this system is grounded in an observer's point of view and his or her response potential, it may be said to incorporate an egocentric (or relative) frame of reference. The spatial information within the perception-action system is characterized by rapid availability and high precision. Furthermore, once an action is performed, the record of the precise information that supported that response would be expected to decay rapidly, especially when the perception supporting the action is altered (i.e., when the context is changed). Rapid decay and context specificity free the system for ongoing activity. However, it need not be a case of "out of sight, out of mind" if there is a record of experience from a second system.

The second system posited by Creem and Proffitt (1998) is a cognitive system dedicated to the development and maintenance of multipurpose internal representations of experience. It is this system that is theoretically involved in the production of verbal estimates of geographic slant and other spatial properties; specifically, the estimate is a symbolic manifestation of the hill's incline. The functioning of this system is explicit, meaning that it is in the realm of awareness, judgment, and contemplation. The representation resulting from this system is flexible, and thus, it can accommodate different frames of reference. Nevertheless, because the representation identifies or describes an object or event, the system involved in developing it is highly compatible with object-based (intrinsic) and global (absolute) reference frames. Such representations apparently work on a sufficiency principle in terms of spatial determinacy; they supply spatial gist sufficient for general purpose. Coding is relatively slow compared to coding location for action, but the payoff in terms of longevity of the representation is quite significant.

To enhance their theory with neural plausibility, Creem and Proffitt (2001a) linked the perception-action and cognitive systems to the two anatomical pathways projecting from the primary visual cortex. Fully cognizant of the fact that information from the two streams are interactive at some point, they associated the cognitive system with the ventral stream, referred to functionally as the "what" system because it is intimately involved in object identification by means of vision (Goodale & Milner, 1992; Ungerleider & Mishkin, 1982). Consistent with the scheme, they associated the perception-action system with the dorsal stream, referred to functionally as the "where" system because of its involvement in providing object location independent of identity (Ungerleider & Mishkin, 1982) or the "how" system because of its support of visually guided action (Goodale & Milner, 1992).

Categorical Versus Fine-Grain Spatial Memory

In this dual coding account, categorical processing involves a rapid, virtually automatic coding of location relative to a spatially defined region, whereas fine-grain processing entails a more time-consuming, effortful process that specifies a particular location relative to the entire range of spatial possibilities. This contrast between coding processes is the essence of the category adjustment model developed by Huttenlocher and her colleagues (Huttenlocher, Hedges, & Duncan, 1991; Huttenlocher, Hedges, & Vevea, 2000) and expanded into a developmental theory by Newcombe and Huttenlocher (2000).

Basically, the category adjustment model is designed to achieve a theoretical rapprochement between two well-established facts: First, spatial locations are often remembered with considerable accuracy without much effort (Anooshian & Seibert, 1996; Hasher & Zacks, 1979), and second, bounded regions have a distorting effect on memory for direction and distance (Acredolo & Boulter, 1984; Allen, 1981; Stevens & Coupe, 1978). The category adjustment model accommodates these findings by positing the memory for location is a joint function of fine-grain processing, which yields precision, and categorical processing, which yields proximity.

A fundamental assumption of the model is that internal representations of spatial location are unbiased; no doubt, a system that provides a veridical record of location had certain evolutionary advantages over a system that includes inherent distortion. However, even unbiased representations are characterized by a degree of uncertainty, which in the case of fine-grain coding is reflected in a distribution of potential locations dispersed around the true value. When that representation is referred to in the act of estimating a location, the fine-grain value that is retrieved is one sample from that distribution of potential locations.

Categorical coding is a story of boundaries and prototypes. A category is defined by the range of fine-grain values within its boundaries and is assumed to be perceived effortlessly by the observer. The prototype is the center or middle of the distribution of fine-grain values within the boundary-defined category. As with fine-grained information, boundaries may be ill defined, and in such cases, they may be represented as a distribution of possible values. Ill-defined boundaries necessarily result in uncertain prototypes, which also may be conceived of as a distribution of potential values. Again, it is assumed that these distributions are sampled during retrieval.

According to the model, when an individual produces an estimate of a previously experienced location, faster decaying fine-grain memory and more robust categorical memory act as a dynamic duo in a somewhat compensatory fashion. The more uncertain the fine-grain information, the greater the adjustment of estimated location consistent with categorical information. The literal adjustment is a matter of truncating at category boundaries and weighting the fine-grain value with the prototypic value. With unbiased representations, such truncation and prototypical weighting will inevitably reduce response variance and therefore constrain overall error.

Although the model has been applied in a variety of experimental studies, its foundation was laid by a series of studies employing the simple laboratory task of remembering the location of a dot in a circle (Huttenlocher et al., 1991). In this task, it was hypothesized that observers impose implicit horizontal and vertical boundaries that divide the circular field into quadrants. The quadrants serve as categories, and the center of these quadrants are considered the prototypic values. Thus, the basic prediction of the model was that observers' memory-based estimation of dot location would be displaced slightly toward the middle of quadrants. The model provided an excellent fit to the data. In other words, memory for a single location in the circle was systematically shifted so that remembered location was biased toward the center of imaginary quadrants of the circle.

As originally posited, the distinction between categorical and fine-grain coding was not associated with corresponding neural structures. However, Newcombe and Huttenlocher (2000) entertained the idea that these two means of coding location might map onto the theory of hemispheric differentiation originally put forth by Kosslyn (1987).

Categorical Versus Coordinate Spatial Memory

This account of spatial memory originally included separate systems, although in its current incarnation as a computational model it involves dual processes that regulate attention toward specific task demands (Chabris & Kosslyn, 1998). Similar to the category adjustment model, the theory contrasts a rapid, automatic process for categorical coding with a more deliberate, effortful process for coordinate coding (Kosslyn, 1987, 1994; Kosslyn, Chabris, Marsolek, & Koenig, 1992). Processing involving spatial classification or categorization is considered to have consequences that are more robust and longer lasting than those involving precise information about the magnitude of spatial properties (such as size, distance, and direction).

However, unlike the category adjustment model, this theory is firmly grounded in visual system neurophysiology. Categorical coding is predominantly the domain of the left hemisphere with a bias toward information processed along the ventral pathway, which mainly receives input from small, nonoverlapping retinal receptive fields. In contrast, coordinate coding information is mainly processed in the right hemisphere with a bias toward information processed along the dorsal pathway, which mainly receives input from large, overlapping retinal receptive fields.

The theory is supported by results from experiments in which observers made either categorical or coordinate judgments about a stimulus display (Kosslyn et al., 1989). For example, in a task involving a horizontal bar and a dot, observers had to respond whether the dot was above or below the bar (i.e., a question about categorical relations) or whether it was greater or less than a specific reference distance (2 cm) from the bar (i.e., a question about coordinate relations). The matter of hemispheric specialization was addressed by comparing speed and accuracy of responding when the display was presented in the right visual field for left hemispheric processing versus the left visual field for right hemispheric processing (Hellige & Michimata, 1989; Kosslyn et al., 1989). Consistent with the theory, categorical judgment was facilitated by initial left hemisphere processing, whereas coordinate judgment was facilitated by initial right hemisphere processing.

Taxon Versus Locale Systems

Although the terminology is from the cognitive mapping theory of O'Keefe and Nadel (1978), this distinction involves a convergence of various frameworks and theories, each positing a fundamental distinction in the structure of two types of memory. In various guises, this distinction has been referred to as involving route versus survey memory (Shemyakin, 1962; see also Shelton, chap. 13, this volume), route versus configurational memory (Siegel & White, 1975), route versus place learning (O'Keefe & Nadel, 1978), and network versus vector memory (Byrne, 1982).

A route representation is posited as a series of stimulus-response associations in which the stimuli are proximal environmental objects or features, and the responses are locomotor maneuvers. Unidimensional representations of this type have been described as products of an associative-serial learning process (Siegel & White, 1975) mediated by mechanisms referred to by O'Keefe and Nadel (1978) as taxon (stimulus-response) systems. Thus described, route memory may be considered spatial in its consequences but not in its content. In contrast, a survey representation is posited as a cognitive map, that is, as knowledge of a set of places systematically related by spatial rules (O'Keefe & Nadel, 1978). Multidimensional representations of this type are posited to be the product of a pattern-learning process (Siegel & White, 1975) mediated by a locale (mapping) system (O'Keefe & Nadel, 1978). Thus, survey memory is spatial in both content and consequence.

Considerable advances have been made in the study of spatial memory since the modern instantiation of these distinctions. In particular, cognitive mapping theory has inspired 2 decades of neuroscientific research focusing on the role of the hippocampal formation and related structures in memory, spatial and otherwise (see Burgess, Jeffery, & O'Keefe, 1999; Burgess, Maguire, & O'Keefe, 2002). Although the "taxon versus locale system" terminology is not all that common currently, the distinction itself remains a fundamental one in that it has found contemporary expression in several forms, as, for example, in Easton and Sholl's (1995) distinction between the self-reference system, which codes self-to-object spatial relations in body-centered coordinates, and the object-to-object system, which codes spatial relations among objects in environmental coordinates (see McNamara & Valiquette, chap. 1, this volume).

In neuroscientific studies, the distinction between systems is supported by evidence demonstrating the behavioral dependence of place learning—but not associative learning—on hippocampal function in rats and by evidence showing the differential activation of hippocampal and medial temporal lobe areas in neuroimaging studies of humans who are processing place information (Burgess et al., 2002). In cognitive studies with humans, the distinction between self-reference and object-to-object systems is supported by data showing different response accuracy and latency patterns when research participants must point to a set of locations after imagined movement (Easton & Sholl, 1995). Specifically, with regularly structured arrays of objects (e.g., objects arranged in a circle or square), observers' pointing behavior shows that they preserve object-to-object memory as they imagine moving without changing direction; with irregularly structured arrays, in contrast, their pointing behavior shows that they rely on memory for self-to-object relations as they imagine moving without changing direction (Easton & Sholl, 1995; Rieser, 1989).

Differentiating Between Systems or Processes

According to the preceding accounts, different systems or processes for spatial memory can be distinguished from each other in a variety of ways. Given the emphasis on brain-cognition relations over the past decade, it is inevitable that distinctions based on brain structures or neural systems come to mind. Nevertheless, behavioral measures provide powerful and sensitive means of distinguishing between systems as well.

Neurally Based Distinctions. Neurally grounded distinctions between systems or processes involved in spatial memory can be based on traditional behavioral measures or, presumably, on indicators of differential neural activity. As mentioned previously, Kosslyn et al.'s (1989) tests of hemispheric specialization involved examining speed and accuracy of categorical versus coordinate responding following stimulus presentation to either the right visual field (and left hemisphere) or the left visual field (and right hemisphere). Similarly, the tendency to distort remembered location toward category prototypes, which is characteristic of categorical coding in the category adjustment model, has been compared after right versus left visual-field presentation. Although it may prove rather challenging because multiple means of coding occur simultaneously, it seems feasible to test predictions about hemispheric specialization in fine-grained or coordinate versus categorical processing using techniques for assessing differential neural activity, such as functional magnetic resonance imaging and especially high-density event-related potentials (see Morris & Parslow, chap. 10, this volume; Shelton, chap. 13, this volume).

Of course, the distinction between taxon systems and the locale system is built on a neural foundation (O'Keefe & Nadel, 1978). Yet in truth, much of the research generated by cognitive mapping theory has focused on the role of the hippocampus rather than on distinguishing between taxon and locale systems. Ablation and electrophysiological recording studies in animals have firmly established that the hippocampus is involved in place memory (e.g., Bures et al., 1999), and neuropsychological and neuroimaging studies with humans (e.g., Maguire, Frith, Burgess, Donnett, & O'Keefe, 1998) have substantiated and elaborated on that conclusion.

Behaviorally Based Distinctions. As with most memory research, the behaviorally based dependent measures typically used for this purpose reflect the accuracy and speed of responding. The perception-action system in Creem and Proffitt's (1988) theory, the taxon system in O'Keefe and Nadel's (1978) theory, and categorical coding in Huttenlocher et al.'s (1991) model and in Kosslyn et al.'s (1992) model are characterized by more rapid processing than are the cognitive system, locale system, fine-grain coding, or coordinate coding, respectively. Thus, exposure time to spatial stimuli should have more of an impact on the accuracy of verbal estimates compared to that of motor estimates, more of an influence on fine-grain information relative to categorical information, and more of an influence on the accuracy of coordinate judgments than on that of categorical judgments.

In addition, the two means of representing spatial relations are posited as differing in robustness, referring to both the effort required for coding and the decay rate of the resulting representation. The perception-action system, taxon system, and categorical coding are described as automatic or, at least, requiring less attention and effort than the cognitive system, locale system, fine-grain coding, or coordinate coding. Thus, the influence of reduced attention through some manipulation such as a dual-task procedure should be much more in evidence with the cognitive system, fine-grained coding, or coordinate coding than with the perception-action system or categorical coding. With respect to decay or degradation rate, in general it is proposed that the perception-action system, fine-grain coding, and coordinate coding are characterized by more rapid loss of information. Thus, the products of these memory processes should be more affected by delay between exposure and responding than should be products of the cognitive system or categorical coding.

Central to yet another possibility for distinguishing between the two means of coding spatial relations is the predicted contrast between remembered or estimated values as a function of actual metric values. Plotting estimated location, incline, direction, or size as a function of actual location, incline, direction, or size across a range of stimulus values provides a relational gradient that can serve as a signature function for a particular system or process. The contrasting functions predicted by Creem and Proffitt (1998) for the perception-action and cognitive systems are clearly laid out. The perception-action system should produce a tight-fitting linear relation with the function's intercept at zero. Generally, estimates produced by the cognitive system should also be linear but with the functions' intercept above zero, thus reflecting constant overestimation. However, if extreme values were included (e.g., estimates of flat ground or of a vertical cliff in the estimation of incline), the function would reflect quadratic curvature at the extremes, as these values would, no doubt, be estimated with metric accuracy. Huttenlocher et al. (1991) predicted different signature functions for fine-grain and categorical coding. Estimates based on fine-grain coding should yield an essentially linear function with intercept near zero and variability reflecting the uncertainty involved in the representation. Estimates based on categorical coding should yield a cubic function (per category), with low values overestimated and higher values underestimated toward the prototype. Clearly, at first blush the predictions made by Creem and Proffitt's (1998) model are not altogether compatible with those made by Huttenlocher et al.'s (1991) model. We turn our attention to this matter in the next section.

COMPATIBILITY OF DUAL CODING ACCOUNTS

In the best of all academic worlds, each of these two-system or two-process accounts of spatial memory would be readily compatible with the others, given a touch of sharpening here and a bit of broadening there. Some alignment among dichotomies is apparent. In terms of basic description, the perception-action system in Creem and Proffitt's (1998) dichotomy can be matched with a taxon system (visually based) described by O'Keefe and Nadel (1978). Likewise, the metric accuracy of Huttenlocher et al.'s (1991) fine-grained coding, Kosslyn et al.'s (1989) coordinate system, and O'Keefe and Nadel's (1978) locale system offers the promise of formal similarity, as does the predictable bias in categorical processing characteristic of Huttenlocher et al.'s (1991) and Kosslyn et al.'s (1989) categorical processing.

Yet, despite this alignment, some apparent lack of correspondence remains. Ideally, in this situation 2 + 2 = 2, that is, if the conceptual and empirical basis for one dichotomy were combined with the conceptual and empirical basis for another dichotomy, the outcome would be a single dichotomy. However, if we simply begin with the two dichotomies mentioned initially in the preceding section, some problems appear rather quickly. As we pointed out at the conclusion of the last section, Creem and Proffitt's (1998) model predicts very accurate, unbiased motor estimates of incline reflecting the precision-based functioning of the perception-action system and biased verbal overestimations of incline reflecting the proximity-based functioning of the cognitive system. Although Huttenlocher et al.'s (1991) category adjustment model has not been applied to incline estimation, its predictions are clear. Bias associated with categorical coding would lead to the overestimation of small angles and the underestimation of large ones (with "small" and "large" referenced to the categorical prototype).

We assumed that the systems or modes of processing described in the Creem and Proffitt (1998) model and the Huttenlocher et al. (1991) model were sufficiently robust to apply to laboratory versions of field situations and sufficiently general to encompass a range of visually based estimation tasks (e.g., estimation of azimuth, height, and distance in addition to estimation of incline). Using these assumptions, we conducted experimental studies in search of the signature functions predicted by the models.

A preliminary study provided a very simple test of whether small angles and heights would be overestimated and large angles and heights underestimated in verbal estimation tasks (Allen, unpublished). Based on evidence that observers automatically tended to subdivide circular regions into 90° categories (Huttenlocher et al., 1991), we assumed that a 45° angle would serve as the prototype in incline estimation and in the azimuth estimation tasks. By logical extension, we also assumed that the middle of an 8-foot-tall wooden board would serve as the prototype in the height estimation task. Participants estimated from memory two inclines, two azimuths, and two heights, one assumed to be greater than the prototype and one to be smaller than the prototype in each case. To parallel the conditions in Creem and Proffitt's (1998) studies, all estimates of spatial properties in this study were incidental to the intentional task of memorizing letter strings that served to demark the target angles or heights. Although it is not clear how critical incidental learning remained in subsequent studies by Proffitt and his colleagues (e.g., Wraga et al., 2000), it was posited as playing an important role in yielding unbiased motor estimates in the early studies.

Results from the incline and azimuth estimation tasks were very similar. When the target incline was small (6°), verbal estimates were higher than motor estimates (14° overestimation vs. 7° overestimation, respectively, on average). However, when the target incline was extreme (53°), verbal estimates were lower than motor estimates (20° underestimation vs. 5° underestimation, respectively, on average). Similarly, when the target azimuth deviated from straight ahead by a small angle (10°), verbal estimates were higher than motoric estimates (15° overestimation vs. 2° overestimation, respectively, on average). Yet when the target azimuth was more discrepant from the participant's heading (55°), verbal estimates were lower than motoric estimates (13° underestimation vs. 2° underestimation, respectively, on average). The height estimation data varied from this pattern. Verbal estimates were significantly lower than motoric estimates for both the 36-in. target (18.5 in. underestimation vs. 7.8 in. underestimation, respectively, on average) and the 72-in. target (12.2 in. underestimation vs. 5.0 in . underestimation, respectively, on average).

These findings supported three important conclusions. First, the similarity between the incline and azimuth estimation data supported the idea that the similar underlying visually based estimation processes apply to each. Second, the pattern of overestimation of small target values and underestimation of large ones in incline and azimuth estimation tasks were perfectly compatible with the categorical biasing effects described by Huttenlocher et al.'s (1991) model. Third, the data showed bias in motor estimates in all three tasks, which according to the Creem and Proffitt (1998) model should be unbiased.

Bolstered by these findings and those of Franklin, Henkel, and Zangas (1995); Montello, Richardson, Hegarty, and Provenza (1999); and Newcombe and Huttenocher (2000) showing categorical bias in a variety of spatial memory tasks, we embarked on a model-based examination of verbal and motor estimates from incline, azimuth, height, and distance estimation tasks. The category adjustment model provided a way of determining the interplay of both fine-grained information, hypothetically from the perception-action system of Creem and Proffitt (1998) or the coordinate system of Kosslyn et al. (1989), and categorical information, hypothetically from the cognitive system of Creem and Proffitt (1998) or the categorical system of Kosslyn et al. (1989). In this study, we obtained participants' estimates from memory to multiple targets along the target dimension, which are necessary to evaluate the fit of the model. Thus, in this study participants made verbal and motor estimates to five inclines (4°, 24°, 43°, 68°, and 86°), five azimuths (2°, 24°, 49°, 71°, and 88° to the left or right), five heights (distributed around each participant's eye height), and five tabletop distances (distributed within each participant's reach). As before, we assumed 45°

would be the prototypic value for the two angle-estimation tasks; we took eye height to be the prototype for the height estimation task and half the participant's reach as the prototype for the distance estimation task. A subset of incline estimation trials were implicit so that we could subsequently determine whether implicit versus explicit estimates differed. Comparisons revealed that they did not.

The category adjustment model posits that estimated location (i.e., $E[R]$) is a weighted average of fine-grained and categorical information expressed as follows:

$$\mathrm{E[R]} = \lambda\mu + (1 - \lambda)p. \tag{1}$$

In this statement, μ is the true location of the object, p is the expected prototype location, and λ represents the relative weight of the fine-grained information.

The central idea expressed in the model is that uncertainty with regard to fine-grained information results in greater reliance on categorical information, referring to the "pull" of the prototypic value in the category. Here are the specifics. The variable M represents the memory recollection on any given trial; it is assumed to be normally distributed about μ, with standard deviation, S_M, corresponding to the uncertainty of the information encoded into memory. Likewise, the category prototype is signified by the random variable P, with mean, p, and standard deviation, S_P, representing the uncertainty of recollection of the prototype. If only the fine-grained information were used in computing an estimate, that estimate would be unbiased because M is centered on the actual value m. However, uncertainty typically creeps into memory, leading to the integration of categorical information (p) into the estimate, thus yielding bias.

Consistent with Huttenlocher et al.'s (1991) original model, we assumed that λ, or the weight of the fine-grained information, is an increasing function of S_P/S_M. Given this relationship, λ should be close to 1.0 when uncertainty about fine-grained memory values is small, and λ should be close to 0 when uncertainty about fine-grained memory values is large.

At this conceptual juncture, our colleague Doug Wedell (personal communication, April 2002) brought to light an important point about uncertainty pertaining to prototype information and uncertainty pertaining to fine-grained information. Specifically, he pointed out that although it is reasonable to assume that certainty about prototypic information is unaffected by where the target falls along the relevant dimension, certainty about fine-grained information may well be influenced by target magnitude. In psychophysical tasks, uncertainty is typically reduced at the endpoints of the range of values (Luce, Nosofsky, Green, & Smith, 1982). The increase in uncertainty toward the middle of a linear series (or conversely, the decrease in discriminability at the endpoints of a series) indicates that stimulus discriminability, and hence weighting of fine-grained memory (λ), should be maximal at the endpoints of the natural category (i.e., 0° and 90°).

With this point in mind, we fashioned a Wedell–Haun–Allen modification (WHAM) of the category adjustment model. We used a simple quadratic function to approximate the aforementioned affect, predicting fine-grained memory weight as a function of the distance between the true angle and the protoype:

$$\lambda = a + b(\mu - p)^2, \tag{2}$$

where a and b are constants. When b = 0, then the relative weighting of fine-grained and protoype information does not vary with stimulus value. Positive values of b would then capture the increased weight given to fine-grained information when values are extreme. Increases in the value of a would reflect generally greater weighting of fine-grained memory.

In the category adjustment model, the focus is on bias or how the estimates deviate from the actual values. Substituting the expression for λ from Equation 2 into Equation 1 and solving for bias yields the following equation that we used to fit the data:

$$\mathrm{Bias(R)} = (\mu - p)(a + b(\mu - p)^2 - 1). \tag{3}$$

Three values are free to vary in Equation 3: p, representing the location of the prototype, a, representing the general weighting of fine-grained information, and b, representing how the weighting of fine-grained memory information changes as a function of distance from the prototype.

Motivated by curiosity, we decided first to apply this model to the incline estimation data from Creem and Proffitt's (1998) Experiment 1 and from our own preliminary study (Allen, unpublished). All estimates had been made without vision shortly after viewing the incline without instructions to remember the angle. As shown in Fig. 3.1, the model provided a good fit to the data ($R^2 = .980$ for the verbal estimates and .955 for the motor estimates). This outcome provided ample motivation for us to proceed with fitting the data from our incline, azimuth, height, and distance estimation tasks.

Consistent with expectations based on our preliminary study, the model provided a good fit to the data from the incline and azimuth estimation task. For example, we obtained a fit of $R^2 = .939$ for all 20 data points simultaneously, with the same prototype for three conditions and a unique prototype for motor estimates of incline. The incline and azimuth estimation data are shown in Fig. 3.2. Thus, verbal and motor estimates of incline and azimuth in our studies showed effects of both fine-grained and categorical coding.

We were a little surprised to find that motor and verbal estimates of height and distance could not be modeled using the category adjustment model (with or without WHAM), principally because a prototypic value re-

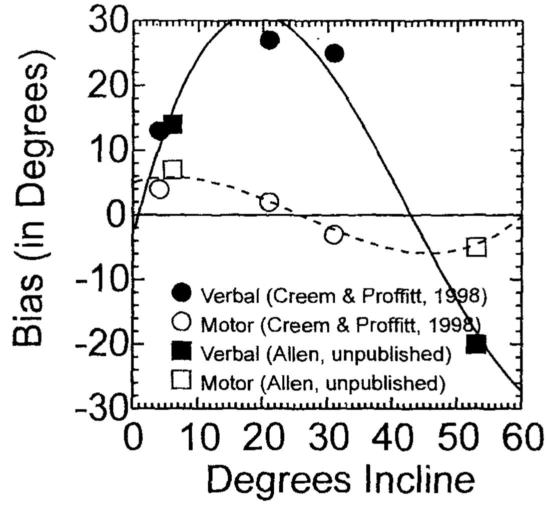

FIG. 3.1. The Wedell–Haun–Allen modification version of the category adjustment model fit to verbal and motor estimates of incline from Creem and Proffitt's (1998) Experiment 1 (three target values) and Allen (unpublished) preliminary study (two target values).

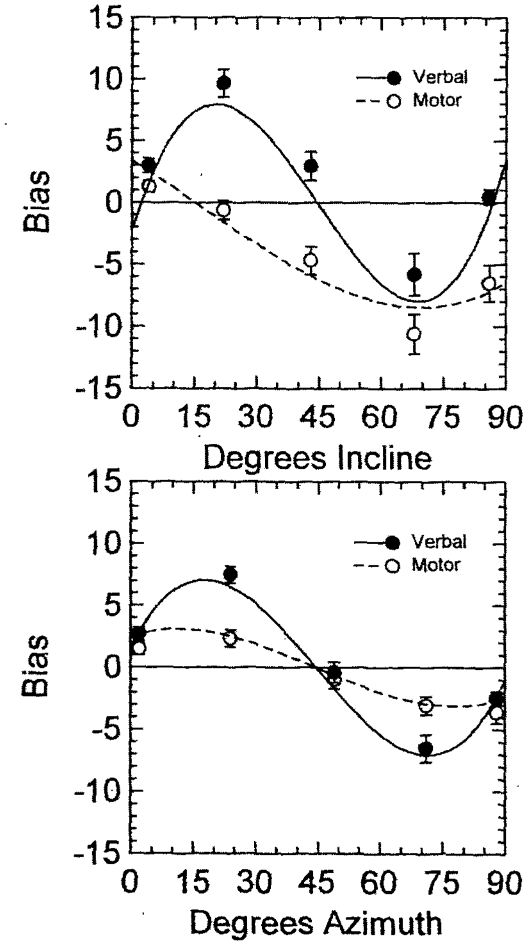

FIG. 3.2. The Wedell–Haun–Allen modification version of the category adjustment model fit to verbal and motor estimates of incline (top panel) and azimuth (bottom panel) to five target values.

mained elusive. Although this outcome was consistent with results involving height estimation from our preliminary study, we understand that it stands in contrast to results in a comparable distance estimation task reported by Newcombe and Huttenlocher (2000). We are uncertain as to what aspects of method led to the disparate results, although our attempt to base prototypic values on each individuals height and reach may well have had a lot to do with it. Nevertheless, it is clear that both data sets show bias, and in our case, the bias is apparent in verbal and motor estimates (see Fig. 3.3).

Because we had originally expected motor estimates to be unbiased, we did an additional study to establish the reliability of the categorical bias effects in motor estimates of azimuth. Participants were asked to estimate azimuth to nine targets distributed in a 180° response field. Additionally, memory load, delay between presentation and estimation, and interference between presentation and estimation were varied. Results showed predictable categorical bias in all conditions. Contrary to our expectations, memory load and interference had very little influence. Our WHAM variation of the category adjustment model provided a respectable fit to these data (Table 3.1).

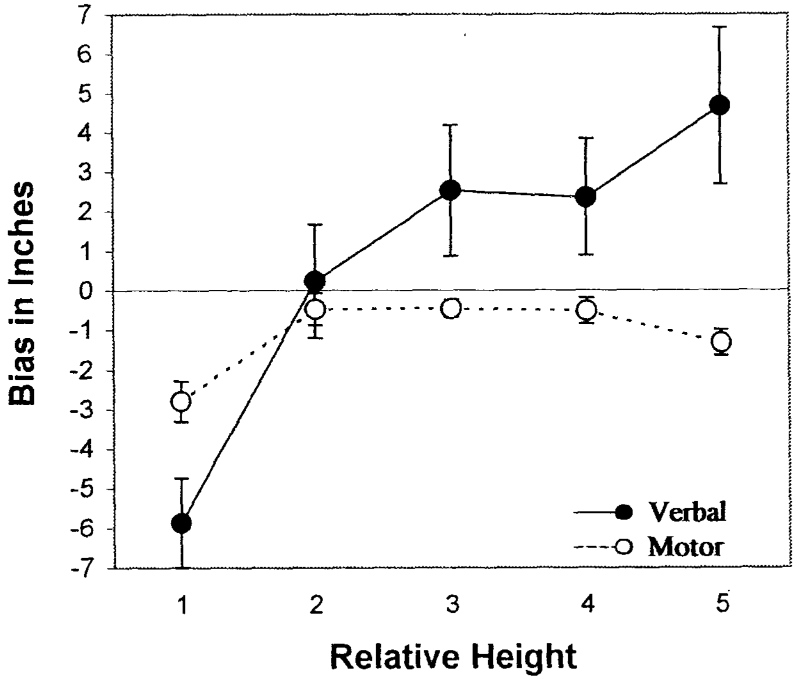

FIG. 3.3. Bias for verbal and motor estimates in a height estimation task as a function of five target values. Values were selected for each participant individually based on eye height (which is portrayed as relative height).

TABLE 3.1

Fit of WHAM Version of the Category Adjustment Model to Motor Estimates of Azimuth (Nine Target Values) under Various Conditions of Processing Load

	Low Processing Load			*High Processing Load*		
Model Fit	No Delay	Delay	ASL Task	No Delay	Delay	ASL Task
R^2	.857	.907	.837	.818	.538	.879

Note. WHAM = Wedell–Haun–Allen modification; ASL = American Sign Language task during delay.

Taken together, the results from our experimental studies suggest an uncomfortable marriage between the two models we set out to examine. On one hand, neither the unbiased motor estimates that Creem and Proffitt (1998) attributed to the perception-action system nor the consistent verbal overestimates that they attributed to the cognitive system were in evidence. Hence, it could be argued that their dual-system account was not supported. On the other hand, the interaction between fine-grained and categorical information that was observed is consistent with the interaction (Bhalla & Proffitt, 2000) between the perception-action and cognitive systems that Proffitt and his colleagues (e.g., Creem & Proffitt, 2001) have posited. Thus, despite the failure to obtain the signature functions predicted by distinction between perception-action and cognitive systems, we did indeed find the estimates were influenced by two factors: fine-grained and categorical influences. Basically, our data must be interpreted as showing rapid influence of categorical bias on location coding.

In the final analysis, the chief source of conceptual incompatibility between the models we examined is not to be found in the data we presented showing categorical influences on both verbal and motor estimates. Instead, it is found in the characterization of the fine-grained information that yields precision in spatial memory. In Creem and Proffitt's (1998) model, the perception-action system is the source of precision, exactness that is lost as the vividness of perception fades and the biasing influence of the cognitive system grows. In Huttenlocher et al.'s (1991) model, fine-grained coding consistent with a coordinate system is the source of precision, exactness that is gained only as additional time and effort reduce uncertainty and concomitant reliance on categorical information. These descriptions do not suggest the same two-system or two-process account of spatial memory.

DUAL-CODING ACCOUNTS RECONSIDERED

At this point, the number 2 has successfully retained its intriguing qualities, especially if we examine various models two by two. With its differentiation between fine-grained and categorical coding, the category adjustment model of Huttenlocher and colleagues (Huttenlocher et al., 1991; Newcombe & Huttenlocher, 2000) is a prime candidate for providing common ground for all dual-coding accounts. The model provides a theoretically potent and empirically valid means of examining fine-grained and categorical influences on spatial memory. However, it does not provide an unambiguous conceptual umbrella for all of the two-system accounts simply because, as originally put forth, it does not discriminate between potential sources of fine-grained information. It can be used to model the interplay of rapidly degrading perception-for-action information with more enduring categorical information as readily as it can be applied to model the interplay of categorical information with more slowly discerned coordinate information.

Thus, closure is elusive on the issue of a unifying two-system scheme. Are there viable alternatives to the dual-system account? In response to this question, we the authors are of two rather disparate views, both of which involve some unusual mathematical expressions.

2 + 2 = 1. It is never wise to dismiss a parsimonious account prematurely. Is it possible that there is a single spatial memory system? First, consider that reliance on comparisons between verbal and motor estimates of spatial properties may not be ideal for resolving the one- versus two-system question. A line of thinking that can be traced back to the 18th-century philosopher George Berkeley (Luce & Jessop, 1949) would have us considering the possibility that verbal estimates will be less precise than motor ones because they are phenomenologically less similar to the actually estimated medium—specifically, space—which Berkeley and others argued to be defined and perceived primarily through touch as a basic informant. Estimating a spatial property motorically means to estimate a property within its own dimension. In the tasks described previously, motor estimates had the same spatial scale as the estimated stimulus. For every degree along the estimated stimulus dimension, a participant's hand had to move a degree to make a correct estimate. Therefore, the response is highly related to the estimated stimulus dimension. Estimating the same stimulus verbally means to translate a stimulus property into a dimension and scale that is an abstract version of the original stimulus dimension. Although an accurate communication of a spatial property is an important interactive skill, achieving this accuracy may not be a matter of spatial memory per se. To create a stronger case for dual systems, future studies should at least compare action-related and abstract estimates with the same underlying dimension and scale.

Generally, bias is considered the result of top-down influences on coding. Consistent with this view, different bias patterns in verbal and motor responses to the same stimulus would justify proposing two different underlying memory systems (Bhalla & Proffitt, 1999). However, top-down processes might alternatively influence response production rather than spatial coding. The idea here is that performance differences in tasks involving the same stimulus type across modalities and situations could be caused by response-side factors acting on the same unitary memory representation. On initial consideration, this point may seem vague or trivial. Nevertheless, the study of spatial cognition has long been plagued by the implicit notion that there are as many different types of spatial memory as there are experimental tasks. This simply cannot be the case.

There may be merit in positing a single highly flexible memory system for spatial information that could support a vast variety of tasks. Conceptually, the distinction between this view and a poly-memory systems view can be portrayed as in Fig. 3.4. A single-system approach would predict that structured manipulations of stored spatial information should be detectable in results from all spatial tasks. A poly-memory system approach would predict that structured manipulations of the stored information in one store would not necessarily be detectable in responses based on spatial information from a different memory store.

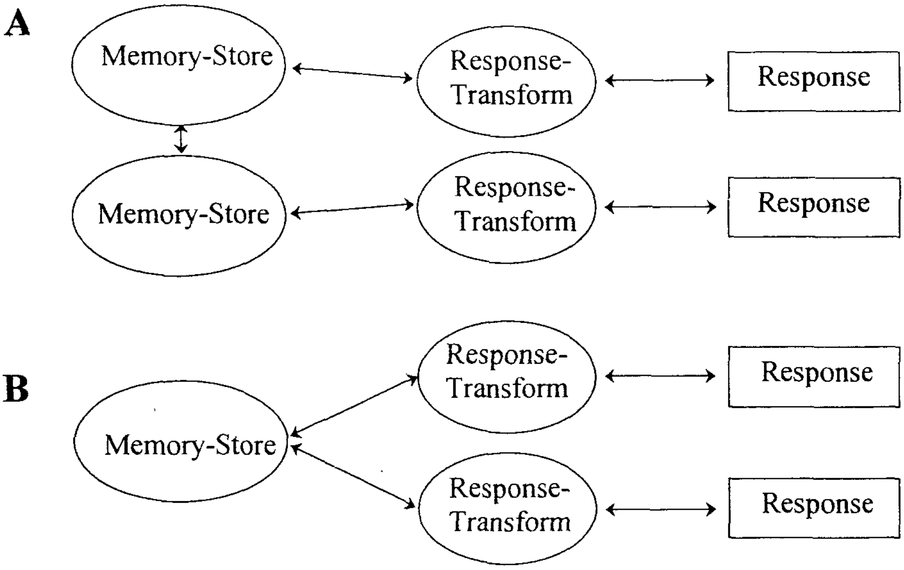

FIG. 3.4. Dual versus single memory systems for generating verbal and motor estimates of spatial properties.

In a single-system view, working memory plays a major role, as information from a singular flexible record of experience is transformed into a representation necessary for specific task demands. According to this view, differences in bias patterns would be due to the task-specific representation that is created based on information that is stored in a single, perhaps unbiased spatial memory system. Accordingly, precision in spatial memory would result from situations in which the unitary mnemonic record of locaion is highly valid (because of salience and trace strength), and demands for precision are great. In contrast, proximity would result from situations n which either the mnemonic record of location is not so valid, but the demands for precision are high, or the mnemonic record of location is highly valid, but the demands for precision are low.

1 + 2 = 3. This odd bit of math reflects the possibility that the dual sysems described for spatial memory actually include three different means of coding location, one that is sensorimotor in nature and two that are coneptual. As mentioned previously, the perception-action system described by Creem and Proffitt (1998) and the taxon systems described by O'Keefe nd Nadel (1978) are compatible, although Creem and Proffitt (1998) were oncerned with describing a mechanism for perception supporting immediate action, and O'Keefe and Nadel were concerned with describing mechanisms for associative learning. In some important ways, the input for his type of system is reminiscent of the proposed visual cache in viual-spatial working memory (Baddeley, 1986; Logie, 1995; see also chumann-Hengsteler, Strobl, & Zoelch, chap. 5, this volume; Sholl & Fraone, chap. 4, this volume). Spatial information is maintained briefly in precise form to support action. Over time, the repeated pairing of specific isual experience with specific actions builds up habit strength that supports the behavioral precision characteristic of skilled performance.

Distinct conceptual processes are described in various two-system or wo-process accounts of spatial memory. One of these involves categorical coding (Cream & Proffitt, 1998; Huttenlocher et al., 1991; Kosslyn, 1987), a obust means of remembering spatial information based on the gestalt of he environment encompassing the task. The range of factors influencing he apperception of this gestalt is considerable, but whether the result is a imple distinction between above and below or a more complicated division of surfaces or objects based on proximity or enclosure, the process typially includes a partitioning of space into bounded regions. Remembering patial relations in this way is very economical in terms of the ratio between Effort at encoding and relative accuracy during retrieval; however, it ineed gives rise to the telltale violations of metric and projective relations hat are a source of fascination to researchers and nonresearchers alike. The ther conceptual system involves coordinate coding (Huttenlocher et al., 991; Kosslyn, 1987; O'Keefe & Nadel, 1978), which involves conceiving of bjects or events existing in an abstract space consisting of an infinite number of points organized by a coordinate system. Remembering spatial relations in this way is relatively effortful, but it yields remarkable accuracy.

Thus, in this analysis we arrive at a three-part scheme consisting of a perception-action system, a categorical conceptual system, and a coordinate conceptual system. This should sound vaguely familiar. If we substitute the terms sensorimotor for perception-action, topological for categorical, and euclidean and projective for coordinate, we have the distinctions between different means for coding spatial relations posited by Piaget and Inhelder (1948/1967) a half century ago. In the current zeitgeist, Piagetian theory is considered passé or invalid by nativists and interactionists alike, with considerable disagreement about whether spatial concepts are better considered innate modules to be activated by relevant circumstances or mental constructs built up under relevant circumstances (see Landau, Spelke, & Gleitman, 1984; Newcombe & Huttenlocher, 2000; Newcombe & Sluzenski, chap. 2, this volume). Nonetheless, certain aspects of Piagetian theory are very useful to the general discussion of poly-systemic accounts of spatial memory. Among these are the ideas that (a) perception of spatial relations is supported by a complete elaboration of space, both projective and euclidean, at the sensorimotor level from infancy onward, which would allow for highly accurate motor-based estimates—or responses to—incline, azimuth, and so forth; (b) representation of spatial relations involves distinct topological and euclidean systems emerging at different times but coexisting and interacting from mid-childhood onward, which would allow for long-term memory for spatial relations being influenced by a combination of categorical and coordinate information; and (c) perception of spatial relations is influenced by the reflection or projection of representational systems back on to perception, which would account for slight categorical bias found in motor-based estimates of spatial relations (see Piaget & Inhelder, 1948/1967).

Summary

The study of spatial cognition has advanced significantly as a result of recent conceptual and empirical work. Essential to substantial progress has been attention to theory development, which has been a deficient aspect of this enterprise in the past. Contemporary theoretical work has provided a number of dual-system models to account for human spatial information processing in general and the distinction between proximity and precision in spatial cognition and behavior in particular. We are not yet convinced that any particular two-system account is sufficiently robust to account for the range of findings. Thus, we urge continued theory-based research aimed at distinguishing among one-, two-, and three-system accounts in the quest to achieve a theoretically sound, functionally robust account of spatial memory.

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