CHANGE AND CONTINUITY IN EARLY SPATIAL DEVELOPMENT: CLAIMING THE "RADICAL MIDDLE"

Nora S. Newcombe
Amy Learmonth
Temple University

Debate over change and continuity in cognitive development has revolved around questions of qualitative transitions versus quantitative and incremental improvement. Piaget's stage theory is the best-known example of a change/qualitative transition approach, while both nativism and empiricism have, for very different reasons, taken a continuity/quantitative increment stance. Recent proposals have, however, attempted to transcend this stark dichotomy, in a move that can be termed claiming the "radical middle." This paper presents two examples of developmental analyses in spatial development. These two transitions are characterizable as either qualitative or quantitative, but are best thought of as both. A position of this kind allows for much more precise answers to practical questions about issues such as sensitive periods than would otherwise be possible.

Introductory textbooks routinely present change versus continuity as one of the fundamental questions facing developmental psychology. One aspect of the change vs. continuity issue concerns the predictability of individual differences, a question important in the areas of personality development and intelligence testing, but rarely raised with respect to thinking about basic cognitive processes. A second aspect of the change vs. continuity issue concerns whether development is qualitative or quantitative in nature. The qualitative position, of course, suggests change, while the quantitative position suggests continuity. With respect to this second kind of question, investigators of cognitive development have been sharply divided. Piaget famously argued for change, dividing cognitive development into four stages he described as distinctively different from each other. However, probably nothing about Piaget's theory has been so consistently attacked as his stage characterization (see Gelman & Baillargeon, 1983). By contrast, nativists and empiricists, otherwise so much at odds with each other, both take a continuity stance. Na-

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• **Nora Newcombe**, Department of Psychology, Temple University, 1701 N. 13th St., 565 Weiss Hall, Philadelphia PA 19122-6085; e-mail: newcombe@astro.temple.edu.

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tivists argue for continuity because they see nothing essential as changing in development—they think that development consists solely in the refinement or augmentation of built-in fundamental principles. Empiricists espouse continuity because they see development as consisting in the progressive accumulation of capacity, skills and facts. However, these positions have important flaws as well (e.g., see Elman et al., 1996 for a discussion of problems with nativism and Fodor, 1997 for problems with empiricism).

Are these three theories (Piagetianism, nativism, and empiricism) the only ways to see development? In introductory textbooks, the answer is still yes. But in professional writing in recent years, we have seen an increasing number of attempts to break away from the unholy triumvirate. We have, for example, the representational redescription theory (Karmiloff-Smith, 1992), theory theory approaches (Gopnik & Meltzoff, 1997), variation-and-selection theories (Siegler, 1996), connectionism (Elman et al., 1996), and dynamic systems theory (Thelen & Smith, 1994). These otherwise disparate approaches are all part of an effort to craft a new kind of developmental theory, one that would escape the all-too-familiar pitfalls of the three textbook frameworks. Which will succeed—or whether any will—remains to be seen. (See Newcombe, 1998, for a discussion of the challenges facing connectionism.)

The new approaches, however, share a common element: the idea that the choice between change and continuity is a false dichotomy. There are two senses in which the dichotomy is false. First, the answer depends on grain of analysis. As Thelen and Smith (1994) suggest, there is a view of development "from above" and a view "from below." Viewed "from above," in broad outline, there are obvious and important differences between humans of different ages. Viewed "from below," in fine detail, there are continuous changes going on all the time, many or even all describable in quantitative terms. Second, which side one champions may be more a matter of emphasis than truth. There ARE starting points for development, as nativists remind us, there IS learning, as empiricists stress, and some of that learning IS active, self-guided, and generating of insight, as constructivists insist. These positions are simply not incompatible, although they are often said to be. In this way of thinking, each of the three traditional positions on cognitive development (constructivism, nativism, and empiricism) can be seen as advocating a partial truth. The trick, as in mixing the perfect martini, is to get the proportions just right.

Now, the right mix may vary from domain to domain. Just as, when bartending, one would put more liquor in one drink than another, the relative importance of innate capabilities, direct feedback from environmental contingencies, maturation, and social interaction may vary for different kinds of cognitive development. The aim of this paper is to give a view of how the mix looks for one crucial domain in which all mobile organisms must function, namely, the spatial domain.

The paper begins with a section outlining the four types of spatial coding systems mature humans use. This analysis of adult competence focuses and orients the discussion of spatial development that follows. The second section examines the hypothesis of a qualitative shift in spatial coding in infancy, from egocentric to allocentric coding. A reconsideration of the data, however, suggests that infants are endowed from at least close to the onset of life with three of the four coding systems seen in adults. Yet, although some of the key possibilities are present early, this observation does not argue either for pure nativism or for an unadulterated continuity view of development. The reliance placed on these systems changes developmentally; when coding systems conflict, infants weight the value of the conflicting systems differently than would an older child. This reweighting transforms how the organism acts and allows for a very different functional level of behavior. In sum, this section argues that an apparently qualitative shift can also be analyzed in quantitative terms, but without arguing that quantitative change is all that is going on—quantitative change leads to qualitatively different behavior in functional terms. The third section discusses another apparently qualitative transition in spatial coding recently discovered towards the end of the second year of life, namely, a change to the use of distal landmarks in spatial coding. As in the second section, part of the argument is that qualitative change also has quantitative aspects. Specifically, there is continuity in two senses. First, some simple elements of the system are apparent in the first year of life. Second, fully functional or mature levels of use of the system do not appear until much later than the second year—in fact, not until about the age of seven years. In sum, as with the egocentric-to-allocentric shift, the "view from above" shows qualitative change, but a fine examination of developmental sequence (i.e., the "view from below") makes change appear more continuous. Neither view is truer than the other; they are complementary.

1. How Humans Code Location

Analyzing development in any domain is easier when one has a good idea of the endpoint toward which development is aimed. There is considerable evidence that mature spatial coding is not monolithic, but can be broken down into several systems. A fundamental distinction is that the location of objects can be coded in two basically different although usually coordinated ways: with respect to external landmarks or with respect to the self (see e.g., Gallistel, 1990; McNaughton, Chen, & Markus, 1991; Newcombe & Huttenlocher, 2000; Sholl, 1995).

Externally Referenced Spatial Coding

Coding an object's location with respect to an external frame of reference involves noting its spatial relations to other objects, usually called landmarks, which constitute long-term stable reference systems for specific areas. That is, people's knowledge of stable landmarks provides the basis for short-term spatial coding, for finding one's glasses (e.g., "on the printer"), or searching for lost objects (e.g., "Perhaps I left my glasses on Fred's kitchen table"). Landmarks are frequently well-known and easy to see—buildings such as the World Trade Center or geographic features such as a mountain. But stability is the only absolutely vital attribute for a landmark. A swing set or a stop sign may serve as useful landmarks, as well as the World Trade Center or a mountain.

There are apparently two dissociable systems of externally based location coding. *Cue learning* specifies an association between the to-be-located object and coincident landmarks (e.g., the object is under a box, on a kitchen table, or somewhere in left field). Cue learning cannot always be used to code location, because coincident landmarks are simply not always available. In this case, metric information is needed to code location with respect to landmarks. *Place learning* involves specifying the distance and/or direction of a to-be-located object with respect to distal landmarks.

There are several reasons to think that cue learning and place learning are dissociable systems. First, cue learning appears substantially earlier than place learning in the rat (Rudy, Stadler-Morris, & Albert, 1987; Schenk, 1985). Second, hippocampal lesions disrupt place learning but not either cue learning (O'Keefe, Nadel, Keightley, & Kill, 1975) or the closely related ability to remember objects (Duva et al., 1997; Glenn & Mumby, 1998). Third, studies using single-cell recording techniques have shown that place learning appears to be dependent on "place cells" in the hippocampus (Muller & Kubie, 1987; O'Keefe & Nadel, 1978; O'Keefe & Speakman, 1987).

Viewer-Referenced Spatial Coding

People need to know where they themselves are in the external spatial world, as well as knowing the relations among objects in that world. In fact, not knowing where one is is profoundly disorienting. There are frequent anecdotes regarding people feeling a sense of panic if they emerge from a subway station in a strange city with no idea of where they are facing or how to begin finding a destination. They feel better if they can establish their position: for example, by discovering that they are looking south towards the World Trade Center.

Encoding the position of the moving self is thus an essential aspect of spatial orientation. However, this relation can also be turned around. Coding the position of objects relative to the moving self can also be the basis for maintaining orientation to the world (Gallistel, 1990; Rieser, 1989). Such viewer-referenced coding can operate in addition to or instead of representations using external frames of reference. As with externally referenced coding, there are two different kinds of viewer-referenced coding, one associating location in a rigid and limited way, and the other involving metric coding.

One system of viewer-referenced coding involves describing a location or a route to a location by a pattern of muscular movements that have been associated with the goal. This kind of coding is often called *response learning*, or, in the developmental literature, *sensorimotor coding*. In such learning, an acquired pattern of movements is run off in a fashion unmodified by either the organism's movement in the environment or by observation of the organism's current location with respect to an external frame of reference. For instance, a person may go to the bathroom in the middle of the night following an accustomed, motorically encoded, sequence of steps. There are important limitations of response learning. Such coding is only useful when a person is in exactly the same situation as was in effect when the motor actions that encode location were learned. Thus, when staying away from home, using sensorimotor coding to find the bathroom at night may lead to unpleasant misadventure.

TABLE 1
Possible systems for locating coding

	Ego-Centered	*Object-Centered*
Simple	Response Learning/ Sensorimotor Learning/ Egocentric Coding	Cue Learning
Complex	Dead Reckoning/ Inertial Navigation	Place Learning

There is a more powerful viewer-centered spatial coding system as well. In this system, location is coded in terms of distance and/or direction from a person's current position, and then updated by input regarding movement, using information from vestibular, kinaesthetic, and visual sources (Pick & Rieser, 1982). Such coding of distances and directions of movement is called *dead reckoning* or *inertial navigation*. Many organisms can navigate in undifferentiated environments by retaining a memory for the extent and direction of their movement, even with quite complicated paths (Gallistel, 1990). Thus, for instance, the foraging desert ant leaves its hole and wanders around its rather uniform sandy environment in search of food. Once it finds something, perhaps 100 meters from its nest after following a wandering route as long as 1 kilometer, it turns and proceeds quite directly back to its hole. Its distance errors are typically around 10% and its angular errors on the order of 1 degree.

Summary and Implications for Developmental Theory

As summarized in Table 1, people may know the location of a specific object in the world in a variety of ways: by cue learning (association with coincident landmarks), by place learning (in terms of distance and direction from distal landmarks), by response learning (memory for particular motor movements), or by dead reckoning (adjusting distance and direction from the self using distance and direction of one's own movement).

Place learning and dead reckoning are more powerful and widely useful systems than cue learning or response learning. Given this analysis of mature spatial memory, the key questions for a description of development involve the charting of the emergence of each of these four systems.

This has not, however, been the traditional way to analyze spatial development. A widely investigated hypothesis is Piaget's claim that infants initially encode location in sensorimotor terms and subsequently go through a qualitative shift to allocentric coding, as a result of their physical interactions with the world. This claim is equivalent to saying that infants start with one of the four systems (i.e., response learning), and then make an early qualitative shift to at least one of the other three. The shift has been largely perceived as well supported by research. It has specifically been thought to be propelled by the development of locomotion in the form of crawling (e.g., Acredolo, 1990; Bertenthal & Campos, 1990; Thelen & Smith, 1994). In the next section of this paper, we will examine the evidence. We will then go on to consider the origins of place learning, a question which has only been investigated recently but which is crucial to understanding spatial competence, given the vital nature of the place learning system.

2. A Reweighting Interpretation of Infant Egocentrism

Initial Studies

The systematic study of spatial coding in infancy began with similar experiments by Acredolo (1978) and Bremner and Bryant (1977). In Acredolo's work, infants were seated in a square featureless room with windows on the left and right. A centrally located buzzer sounded, letting the infants know that they could see a person making engaging faces at them, if they turned their heads towards one of two windows. There was one window on the left wall and one on the right wall of the room; infants saw events only on the left (or only on the right) side. Following trials of this kind, the infant was moved along a semicircular path to the opposite side of the room. The crucial data concerned where the infants then looked when the buzzer sounded: to the same side of their body as previously led to the interesting event (thus ignoring the fact of movement) or to the other side (thus taking movement into account). Bremner and Bryant (1977) gave 9-month-olds experience finding an object hidden under one of two identical cloths. The cloths were placed side by side on a table, one to the left of the infant's midline and the other to the right. They then moved the infants to the opposite side of the table. The crucial data concerned whether infants searched under the cloth on the same side of their body as where they had seen the object hidden (a self-referenced coding not taking account of movement), or on the opposite side (now the correct location).

If infants only have a sensorimotor coding system, infants in both kinds of experiments would search incorrectly, on the side defined by their previously correct body movements. This is the "egocentric" choice. Correct choice in this situation can be based on several kinds of spatial coding. Infants can succeed by coding the distance and direction of their movement (i.e., by dead reckoning); such coding is in fact the only option available when infants are studied in environments whose features are carefully placed so as not to provide cues, i.e., with objects placed centrally, or with duplicate objects placed symmetrically along the left-right axis. Infants can also succeed in these studies by coding location using external landmarks, when informative landmarks are available. These can be either coincident landmarks, which allow for cue learning, or distal landmarks, which require place learning. The egocentric-to-allocentric literature has concentrated on studying coincident landmarks (i.e., cue learning). So, in summary, when infants in these studies make a nonegocentric choice, they may be using either dead reckoning or cue learning or both, when cues are available.

When cues are not available, they must be using dead reckoning.

When infants were in an unmarked room (in which correct responding could only be based on dead reckoning), Acredolo (1978) reported that infants of 16 months were successful in turning to the correct side to see the event (i.e., they used dead reckoning), but 6-month-olds and 11-month-olds continued the same movement they had made before (i.e., relied on response learning/sensorimotor coding). When a landmark (a yellow star) surrounded the correct window, and correct responding could be based on cue learning, 6-month-olds continued to make errors evidencing sensorimotor responding. However, about half the 11-month-olds showed correct responses. Some success at 11 months when a coincident landmark is available, but not otherwise, suggests an earlier advent of cue learning than of dead reckoning (at least, dead reckoning across the rotation-and-translation movement used in the study). The data from the Bremner and Bryant (1977) study supported the hint in Acredolo's work that cue learning was just beginning towards the end of the first year and would not be in evidence earlier. They found that, at 9 months, infants continued to search as defined by response learning after having been moved to the opposite side of the table, even when cues marking the correct choice were provided by painting one side of the table black and the other side white.

The findings reported by Acredolo and by Bremner and Bryant seem to support the existence of an "egocentric to allocentric" shift (although it might be better to use the term "nonegocentric" than "allocentric", given that correct responding can be based on more than one kind of spatial coding). Specifically, infants in these studies seemed to search based on response learning, with some infants shifting to cue learning about 11 months, and with a shift to use of dead reckoning sometime before 16 months. However, there is another way to characterize development that does not involve wholesale shifts from one mode of coding to another.

Consider the possibility that infants must learn which spatial coding system to use when response learning conflicts with the other systems, or when dead reckoning conflicts with externally referenced coding. When organisms are stationary (and, of course, early in life, infant motor abilities are very limited), both response learning and cue learning lead to the same (correct) response, and dead reckoning is irrelevant. But when organisms move, response learning is unreliable. Externally referenced systems and dead reckoning generally correspond after movement and either can be relied on when they do. In mature organisms, any conflicts which do arise between external referencing and dead reckoning are usually resolved in favor of the externally referenced systems because, from a functional point of view, dead reckoning is more subject to drift and needs to be calibrated with respect to fixed external landmarks (Gallistel, 1990). Perhaps infants, with limited experience with the spatial world, have access to some or all of the possibilities for spatial coding, but have an initial setting in which response learning predominates. Such a choice would not be maladaptive, because infants *are* initially fairly stationary. But neither would it indicate complete absence of cue learning, or an inability to code self-produced movement. Correcting a misreliance on response learning could be expected in the environment of adaptation, based on direct environmental feedback once active motoric abilities emerge. That is, when response learning fails to locate an object, trial and error should usually reveal that cue learning would have led to the correct choice. Various lines of evidence support this "reweighting" view of infant development.

Early Cue Learning

First, infants show evidence of cue learning rather than response learning when the cues are fairly salient, as one would predict from the idea that their problem is deciding which of two coding systems to use when the systems conflict. Recall that, in Acredolo's initial work, 6-month-olds did not seem to use a coincident landmark (a yellow star around the correct window) to locate the interesting event, seemingly indicating an absence of cue learning; only some 11-month-olds used the yellow star to find the event. Similarly, Bremner and Bryant (1977) found that painting half their table white and half black did not improve 9-month-olds' search for an object hidden under one of two cloths, one on the black-painted side and one on the white-painted side. However, the yellow stars and the white- and black-painted table tops turn out to be insufficiently salient cues to support cue learning. Bremner (1978b) showed that when the *cloths* hiding the objects were white or black, rather than just the table tops, 9-month-olds were able to choose correctly following movement to the opposite side of the table. In addition, Acredolo and Evans (1980) found that both 9- and 11-month olds could make correct choices of where to look for an event when very salient landmarks (stripes and lights) surrounded the correct window. In fact, in the stripes-and-lights condition, infants as young as 6 months did not show definite signs of sensorimotor choices. Instead, they systematically checked both windows as if unsure about the location of the experimenter. This observation suggests that, even at 6 months, salient coincident landmarks are considered relevant to spatial coding. The infants' vacillation also supports the idea that, initially, infants use both response learning and cue learning but have not yet worked out which system to rely on when they are in conflict. In sum, cue learning and response learning are both available at 6 months, and cue learning predominates over response learning by 9 months when the cues are more salient than those used in the initial studies.

Rieser (1979) reported further evidence of the ability of 6-month-olds to use cue learning under particular conditions, and of their lack of knowledge as to how to handle conflicts between the response and the cue systems. Infants in his study lay on their backs, looking up at four covers arranged in a diamond pattern, behind one of which an object was hidden. They were able to use a distinctive cover pattern to find a hidden object after they were moved in a 90 degree rotation on their axis, as long as the cover on the choice dictated by sensorimotor coding was unpatterned. When the covers of both choices were patterned, infants did not consistently use the contrasting pattern information to make the correct choice. However, in this condition, they did not show systematic sensorimotor choices either. Instead, they showed the same mixture of the two choices seen in the 6-month-olds studied by Acredolo and Evans (1980).

The conclusion that infants can use cue learning, that is, associate the location of an object with a coincident landmark, is reinforced by two studies in which coding systems were not placed in conflict. In a well-known study primarily directed at demonstrating early object permanence, Baillargeon (1986) habituated 6- and 8-month-olds to an event in which a toy car went on a track down a ramp and then along a level plane in front of the infants. Following habituation, infants were shown a box placed either to one side of the tracks or on the tracks, and a screen was raised so that the infants could not see that part of the track. Infants who saw the box placed on the tracks looked longer when the toy car emerged from behind the screen (impossible event) than did infants who saw the box placed to one side of the track (either in front or behind). This study shows memory for the location of the box as on or off the track (as well as of the continued existence of the box, an issue in the object permanence debate). Thus, the study strengthens the case for cue learning by 6 months, by showing that it is clearly seen in a situation in which there is no need to choose between systems in conflict.

More recently, McDonough (1999) has shown that 7-month-olds can remember which of two distinctive containers contains an object, even after a minute's delay filled with distraction. Infants in this study were allowed no experience in reaching to containers, thus eliminating response learning in the motor system, and had their visual attention specifically attracted to both locations, thus minimizing response learning in the looking system. They were not moved and hence did not need to use dead reckoning. Thus, this study also shows clear evidence of cue learning at 7 months, at least in a situation where no choice among competing systems is required.

In sum, the data in these studies suggest that by 6 months or so infants code spatial location using coincident cues, as well as in sensorimotor terms. Which system they rely on when the systems are in conflict may be affected by stimulus salience, and by a lack of experience in which system works better.

Early Dead Reckoning

A second kind of data supporting a reweighting interpretation is evidence that infants show dead reckoning rather than response learning when the motions involved are actions, which they have experience actively producing, again congruent with the idea of systems in conflict; since experience with certain kinds of motion is presumably crucial to determining when to rely on each of the available coding systems. The movement infants underwent in the original work by Acredolo and by Bremner and Bryant was quite complex: a combination of rotation (spinning on one’s axis) and translation (movement through space, in this case, on a semi-circular path). Motion of this kind is unlikely to be experienced by nonlocomoting infants, except when being passively carried, a condition under which they generally pay little attention to their location (Acredolo, Adams, & Goodwyn, 1984; Benson & Uzgiris, 1985). Animal work in fact shows that spatially-related hippocampal activity ceases almost entirely when active motion is restrained (Foster, Castro, & McNaughton, 1989). However, fairly early in life, infants can engage in motion around their axis (i.e., turn their heads and trunks from side to side, roll over) and can produce simple lateral motion (i.e., that produced by bodily swaying); they can also perceive their position relative to gravity (i.e., lying down or vertical). Thus, a natural prediction is that infants can take account of simple kinds of movement, which they have experience producing themselves, before they can deal with more complex kinds of movement which they cannot produce. That is, the initial studies may have underestimated infants’ early abilities to engage in dead reckoning.

Several studies support this idea. At 5 months, infants distinguish their own motion along an arc around a stationary object from object motion around themselves while stationary, as well as from conjoint self and object motion (Kellman, Gleitman, & Spelke, 1987). By 6 months, infants do not make egocentric choices when tilted with respect to gravity at training but tested in an upright position (Rieser, 1979), and infants can compensate for rotations to their left and right (Landau & Spelke, 1988; Lepecq & Lafaite, 1989; McKenzie, Day, & Ihsen, 1984). By 9 months, infants can adjust for lateral movement along a line (Landau & Spelke, 1988).

In sum, by 6 months, infants code spatial location using simple dead reckoning, as long as the kinds of motion they need to take into account are kinds they already have experience in actively producing. At first, the motions they produce are limited, but being tilted with respect to gravity and head and trunk rotation do result in changes in spatial location which babies can apparently take into account. Somewhat later, lateral translation can be added to this list, and sometime after that, more complicated paths involving both rotation and translation.

Initial Reinforcement of Response Learning

A third argument for a reweighting approach focuses on the fact that lack of reinforcement of response learning decreases the likelihood of infants' relying on it. In Acredolo's and Bremner and Bryant's studies, the experimenters gave infants several trials of reinforced motoric experience before moving the infant. That is, the baby looked repeatedly, say to the left, and saw an adult making funny faces, or reached repeatedly, say to the right, and obtained an interesting toy. These trials seem likely to strengthen an infant's tendency to use response learning. While repetitions of certain motor sequences after infants are moved may reflect a conception of objects as at the disposal of action, as Piaget thought, it is also possible that more adaptive codings might be evident in situations in which they were not outweighed by the strength of the recently reinforced motor sequences.

One way to distinguish these alternatives is to examine performance following experiences in which infants see objects hidden, but do not search for them. When prior motor movements have not been reinforced by obtaining an object or viewing a funny face, infants of 9 months are more likely to search correctly, although they do not entirely give up on egocentric responses (Acredolo, 1979, 1982; Bremner 1978a). This improvement is evident in environments both with and without landmarks (Acredolo, 1982).

Thus, at 9 months, infants may have some awareness that movement leads to a need to adjust location coding, and some ability to perform such adjustment, even after rotation-and-translation. Their ability to look appropriately—to choose the correct coding system from the conflicting possibilities—is reduced when one of the systems, namely response learning, has been recently reinforced.

Emotional Stress

There is another reason why the Acredolo (1979, 1982) and Bremner (1978a) studies just reviewed may have found better responding than had the initial studies using the paradigms. As well as not experiencing initial reinforcement of motor responses in these later studies, infants were tested at home, that is, in situations in which they likely felt less emotional stress than they may feel in typical laboratory situations. Emotional stress is known to affect spatial learning in rats (Diamond, Fleshner, Ingersoll, & Rose, 1996).

Curious whether the contrast between findings in laboratories and at home was due to emotional factors or to the fact that homes typically contain many more objects (and hence potential spatial cues) than do laboratories, Acredolo tested babies in an unfamiliar office environment—at least as cluttered as a home, but still emotionally stressful, like a laboratory. She found babies making predominantly egocentric choices when tested in the office environment, implicating the role of emotion over the role of a larger number of potential landmarks. Acredolo (1982) provided further support for the role of emotion, showing that, even in a lab environment, 9-month-olds chose correctly rather than egocentrically, following movement to the opposite side of a room, if they were first given an opportunity to play in the environment and, presumably, to feel more comfortable in it. (At least, they chose nonegocentrically when not given prior motor learning—no babies were tested in this study following initial reinforcement trials.)

Why Does Reweighting Occur?

The existence of infant capabilities in cue learning and simple dead reckoning, as well as in response learning, does not imply that there is no developmental change in spatial coding. On the contrary, there seems to be substantial change in the circumstances under which infants of different ages will and will not rely on response learning in cases where such coding conflicts with cue learning or with dead reckoning. According to the view we are advancing, development consists in changes in the importance attached to different types of spatial information when they come into conflict. (Such changes would be represented as "reweighting" in a computational model.) Changes in the cue validity of different types of information seem likely to be driven by success or failure in locating an object when relying on the various possible information sources. What changes in the capacities of infants and in the feedback they consequently obtain from the environment drive a reweighting process?

One possibility is crawling. There are many dramatic moments in the infant's motor development in the first 18 months. The abilities to roll over, to sit up, to grasp, to pull oneself erect, and to walk transform the infant's experience. All might be expected to have some impact on the nature of the child's interaction with the spatial world. However, the motor milestone, which has attracted the greatest attention from researchers interested in spatial location, is crawling. Crawling represents the infant's first acquisition of independent mobility. Thus, it has been suggested that independent mobility has profound effects on the extent to which infants can keep track of their position in the world and of the location of objects following movement.

Several findings have provided support for this hypothesis. At 8 months, infants who can crawl show less sensorimotor responding in the Acredolo (1978) paradigm than non-crawlers (Bai & Bertenthal, 1992; Bertenthal, Campos, & Barrett, 1984). This difference is apparently not attributable to some maturational difference between the groups, because non-crawling 8-month-olds with experience in walkers show less sensorimotor responding than did non-crawlers without walker experience (Bertenthal et al., 1984). In addition, a case study of a child confined to a body cast for the first 8.5 months of life has shown that, after release from the cast and the beginning of independent locomotion, the child showed an abrupt drop in sensorimotor choices (from 60% to 20%) in the Acredolo paradigm.

Motor experience may not, however, be the only experiential factor leading to a reweighting of possibilities. In particular, visual experience may also be relevant. The child confined to a body cast, studied by Bertenthal et al., showed an initial drop in sensorimotor responding (from 100% to 60%) while still confined to the cast, suggesting that it is not *only* locomotion which accounts for a diminution in sensorimotor coding. In addition, children who are blind in infancy are known to experience spatial difficulties, and children who have partial vision, or who had vision early and then lost it, have fewer spatial difficulties than infants profoundly blind since birth (Warren, 1994). These pieces of evidence suggest that visual experience contributes to spatial development, independent of motor experience. Blind infants often show delays in reaching motor milestones, but they do eventually crawl and walk. Yet, their ability to perform many simple spatial tasks can still end up greatly impaired.

A third relevant factor in spatial development may be cortical maturation, although the nature of its role is not yet clear. Bell and Fox (1996) found that infants with more crawling experience had greater degrees of EEG coherence at frontal and occipital sites than infants with less crawling experience, and argued that crawling may reflect cortical maturation rather than exert an independent influence on cognition. A weakness of such an argument is that it would not explain the effect of walker experience found by Bertenthal et al. Another possibility is that the experiences occurring to the mobile child drive a process of brain maturation. Particular real-world experiences may lead to the adoption of certain task strategies, which engage particular brain areas. Experience may even lead to structural change in the nervous system (as argued by, among others, Thelen & Smith, 1994).

Summary

The predominance of sensorimotor responding in Acredolo's and Bremner and Bryant's initial studies seems to depend on factors which affect how infants weight information when coding systems are placed in conflict.

That is, infants' choices among conflicting spatial systems depend on some combination of cue salience, complexity of movement (especially whether or not the movement can be actively produced), whether or not response learning has been recently reinforced, and whether the infant is emotionally secure or under stress. Not every combination of circumstances has been tested, but it seems likely that, at least by 6 months, infants can use both cue learning and dead reckoning with respect to self-produced actions, in addition to response learning.

Some accounts of these findings stress the qualitative shift in functioning observed at this time (e.g., Acredolo, 1988). However, if one thinks of infant spatial development as constituting a shift in how to weight coding systems when they are in conflict, the data on motor experience suggest instead that experience with particular kinds of movement helps to change the importance assigned to sensorimotor versus other coding systems, through positive and negative feedback. After all, it is only when infants move that response learning fails, providing information questioning its usefulness. Thus, experience with gravitation (some of which is available even to the very young infant) is necessary for success in a task such as that of Rieser (1979), experience with rotation around one's trunk is crucial for success in rotational situations of the kind studied by McKenzie and Day or by Landau and Spelke, and experience with taking paths which summate rotation and translation, as occurs in crawling, is crucial for success in the Acredolo situation. Motor experience is not all, however. Both motor and visual experience appear to work, in normal circumstances, to "reweight" the system, with slower development seen both in cases of enforced immobility and of blindness. Behavioral development is accompanied by changes in brain activity, but whether these are maturational, or the results of experiential input, remains to be decisively determined.

Overall, this way of thinking about early spatial development is quite similar to the variation-and-selection model advocated by Siegler (1996) for analysis of cognitive development. The basic idea shared in Siegler's theory and the present argument is that experiences gained through interaction with the physical and social environment allow an existing set of strategies or systems to be tuned to greater efficiency and accuracy. An important feature of the present approach to spatial development is that it is easy to see that the competing approaches might originate for adaptive reasons and be implemented in neonatal neural circuitry. Response learning, cue learning and inertial navigation are all plausibly based on feedback systems in the human brain, systems likely in need of tuning and pruning, but present in some untuned and unpruned form early on. The approach to spatial development is also similar to the thinking of Hirsh-Pasek and Golinkoff (1996) about language development. Hirsh-Pasek and Golinkoff have emphasized changes in the coalition of cues used by infants to identify words in the sound stream and potential meanings for those units. Early on, for instance, acoustic characteristics may dominate, while later on, they are de-emphasized but never discarded. The idea of variation-and-selection is clearly a powerful one in thinking about developmental change in several cognitive domains.

3. Place Learning

The research just reviewed shows that infants can use three of the four systems of spatial coding used by mature humans. However, what are the developmental origins of the most powerful system, place learning, in which distances from various distal landmarks are used to fix location in space? Place learning is known to develop later in rat pups than cue learning, and seems to depend on mature hippocampal circuitry, while other coding systems do not (see Nadel, 1990, for review and discussion). In this section, we explore whether there is also a later emergence of this coding system than of other systems in humans.

There are at least three studies suggesting that place learning may emerge relatively late in human development (i.e., after the initial reweighting which we have argued takes up much of infancy). The earliest was done by DeLoache and Brown (1983). These investigators placed a desired object in one of four identical containers, and then placed the containers, in full view of the child, in various locations in the center of a living room. Thus, to find the object, children needed to code the location of its container using distance and direction from landmarks, such as furniture, in the room. Children as old as 26 months had difficulty finding objects in this situation. They did much better when toys were hidden under distinctive landmarks (when cue learning would lead them to the target).

In a second study relevant to the origins of place learning, Mangan, Franklin, Tignor, Bolling, and Nadel (1994) hid a toy in one of eight identical locations, arranged in a circle on a circular platform enclosed with curtains. Children were disoriented and asked to search for the object. Finding the correct location would require coding of distance and direction from distant landmarks visible above the edge of the curtain. Children younger than 24 months failed to find the object.

A third study was reported by Newcombe, Huttenlocher, Drummey, and Wiley (1998). We had two concerns about the existing work. First, the tasks used by Mangan et al. and by DeLoache and Brown required discrimination among multiple identical hiding containers. Because very young children are generally reliant on cue learning, the presence of multiple identical cues might be confusing, and might distract children from using distal landmarks they might otherwise use. Second, children in both studies moved a good deal about the space before being allowed to search. Hermer and Spelke (1994) reported that, when children less than 24 months are disoriented in space by being turned around several times, they fail to use even coincident landmarks to localize objects, a skill in use from the first year of life. If this is true, disorientation might certainly be expected to disrupt use of the more complex system of place learning as well. For either or both of these two reasons, we wondered if place learning might be evident in children younger than 2 years if they were tested somewhat differently.

Newcombe et al. (1998) therefore examined the development of place learning in a continuous space and when children were not completely disoriented. Children in this study searched for objects in a continuous space (the 5-foot sandbox) in which they were not distracted by the presence of multiple identical hiding containers, which might have led to underestimation of place learning in prior studies. They looked for the hidden toy after they went around the box to the opposite side, a movement which was sufficient to take the accuracy of their searches away from the ceiling-level performance we had found previously, but which was not sufficient for disorientation. One group of children looked for objects in the sandbox with visual access to external landmarks, while a second group did the task in an environment in which landmarks were hidden from view by a circular white curtain. The contrast between accuracy with and without external landmarks visible was crucial for investigation of the development of place learning. If there is a developmental transition, younger children would be expected to show the same degree of accuracy in search when they could see external landmarks as when they could not, whereas older children would be expected to show an improvement in accuracy when they could see the external world.

This study found evidence of developmental change between 16 and 36 months in the use of distal external landmarks (i.e., place learning). Specifically, the data indicated a remarkable contrast between the spatial coding seen in children of 21 months and younger and that seen in children 22 months and older. Children under 22 months did not refine the accuracy of their location coding using external landmarks when these are available, whereas older children did. This contrast was striking in size and apparent abruptness, and especially remarkable in that it was not affected by overall improvement in the basic task; younger and older children searched with equivalent accuracy when external landmarks are not visible. Apparently, the results of DeLoache and Brown and of Mangan et al. were not due simply to children being confused when faced with multiple identical containers or having had their dead reckoning systems overwhelmed; in the present study, children searched under the continuous surface of the sand and walked a relatively simple path around the sandbox. The fact that similar developmental findings emerge both when external landmarks are useful to refine spatial codings which otherwise lack precision (as in the present study) and when they are the only way to locate objects at all (as in DeLoache & Brown, 1983, and Mangan et al., 1994) suggests that the transition is a general one.

A Maturationally-Based Qualitative Shift?

One possible explanation for the existence of an abrupt transition in the use of external landmarks, between the ages of 21 and 22 months, is that it depends on hippocampal maturation. This hypothesis is the one favored by Mangan et al. (1994). Support for it comes from evidence that similar transitions in performance by developing rats in the Morris water maze are due to such maturation, and that human hippocampal maturation continues until about this age (Kretschmann, Kammradt, Krauthausen, Sauer, & Wingert, 1986; Seress, 1992).

Some doubt has been cast on the hypothesis of late hippocampal maturation by Diamond (1990; see also Diamond, 1995), who has studied delayed nonmatch-to-sample, a task which has also been linked to hippocampus. While Overman (1990) found that children could not perform this task until 21 months of age, Diamond argued that the apparently late emergence of the ability was dependent on the fact that success requires means-ends analysis (children must displace the novel object to obtain a reward). When the task was modified to avoid this requirement, success was seen much younger. However, recent data from animal studies show that DNMS performance may not depend on hippocampus but rather on perirhinal cortex, and that DNMS and place learning are doubly dissociable (Duva et al., 1997; Glenn & Mumby, 1998; Kim et al., 1997). So, the hippocampal maturation hypothesis could still be correct.

Quantitative Aspects of the Qualitative Shift

In looking at research on the advent of place learning, it is tempting to conclude that we have found an unequivocal example of qualitative change. This would be misleading, however, for three reasons. First, there are important early precursors of place learning. In particular, one of the abilities involved in place learning is the ability to code distance in continuous space. Toddlers can do this by the age of 16 months in a simple one-dimensional situation (Huttenlocher, Newcombe, & Sandberg, 1994). Even 5-month-old infants notice when an object emerges from a location separated from the location where it was hidden (Newcombe, Huttenlocher, & Learmonth, 2000). Thus, precursors to place learning can be observed early in life, and it may be that a fine-grained study will lead to the identification of small, continuous-seeming steps allowing for the apparently sudden emergence of place learning.

A second problem in arguing strongly for a qualitative transition to place learning is that children of 21 months have not achieved mature competence in place learning. Several investigations have shown that children younger than about 5 years do not perform as well as older children and adults on keeping track of where they have been in an eight-arm radial maze (Aadland, Beatty, & Maki, 1985; Foreman, Arber, & Savage, 1984; Overman, Pate, Moore, & Peuster, 1996) and that children younger than about 7 years do not perform as well as older participants on two adaptations of the Morris water maze for use with human children: finding an object in a circular enclosure and on a very large open field (Overman et al., 1996). Thus, again, finer-grained study is likely to show that many factors condition the continuous approvement from the first appearance of place learning to its mature state.

A third issue to consider before arguing for a qualitative transition to place learning is the possibility that the change might depend on quantitatively accumulating experience rather than, or in addition to, brain maturation. In this case, the age at the apparently qualitative transition might be variable across samples with different kinds of relevant experience. One possibility is that accumulating amounts of experience with upright locomotion, especially as it becomes increasingly less effortful, might be relevant to such a developmental change. It is difficult to see distal landmarks and a to-be-coded location simultaneously when crawling, and pre-walking infants may simply not have the experience necessary to realize the value of such coding. While infants begin to walk at around a year, walking is initially tentative and effortful, and infants at the early stages of bipedal locomotion often look at their feet or at potential nearby supports more than they do at distal objects. The hypothesis that experience with skilled walking is necessary for place learning could be tested by comparing place learning in children who walk early and late.

Another way in which experience might change the age of an apparently qualitative transition is that use of place learning may vary depending on the kind of external landmarks that are available. Children of 16 months apparently use the frame of the sandbox to code location and apparently do *not* use distal landmarks. This contrast might be specific to use of an enclosing geometric shape (cf. Hermer & Spelke, 1994, 1996), or perhaps children begin to use noncoincident landmarks that are fairly close to the to-be-coded location (e.g., the sides of the sandbox) and, with age, realize the value of using increasingly distant landmarks (e.g., objects several feet away, as are most trees or pieces of furniture). Or perhaps the need to code distance from two or more distal objects in order to get a fix on location is key to the developmental lag between distance coding and place learning. Systematic investigation will be required to determine which of these factors, if any, are most relevant. For now, the point is that fine-grained investigation has again a good chance of finding development to look more continuous than it looks when seen from "above" in broad outline.

Conclusion

This paper argues for a simple thesis. Characterizing cognitive development as involving either change or continuity, or as involving only one kind of underlying mechanism (be it environmental feedback, neural maturation, active exploration or cultural scaffolding) is no longer a scientifically productive strategy. We now have the theoretical and experimental tools to attack the question of just how these elements are mixed in particular domains of development, while maintaining a simultaneous awareness of both the quantitative and qualitative aspects of developmental change. In support of this thesis, we have offered two examples in this paper of analyses of particular issues in spatial development. We have argued that, in each case, there is evidence of both substantial continuity and substantial change, depending on the grain of analysis and the functionally appropriate criterion of change.

It is always exciting to find a benchmark in development, and the transition away from egocentrism in the first year of life or the appearance of place learning at 21 months are potentially such benchmarks. However, viewing either transition as a qualitative change in broad outline does not preclude taking a close look at the precursors of the ability, at the factors conditioning its age of emergence, and at the growth the nascent ability takes to mature levels. Examined in this way, development looks much more continuous. However, neither the qualitative nor the quantitative view is correct when emphasized in isolation from the other. Achievements have precursors, first emergences, and times at which they reach mature levels. Each such achievement is somewhat conditioned by exact testing protocols and methods. Rather than rejecting the notion of competence altogether, as done by Thelen and Smith (1994) or wrangling interminably about the "true" definition of competence, as done in the disputes between classical Piagetians and those who have demonstrated early success on Piagetian tasks (see Chapman, 1988 for an account from the Piagetian side), we ought to celebrate the informativeness of "thick" (and precise) description of developmental phenomena. Such a strategy leads to the formulation of hypotheses specific enough to be testable, and, even more importantly, to the formulation of a complexly interactionist account of development that rejects simple dichotomies such as change versus continuity.

In rejecting the change versus continuity dichotomy, we also help to address the question of the importance of infancy in development. A continuity view tends to foster the idea that infancy is a crucial period of development, during which all the fundamental elements of cognitive (or social) life are determined. A change view, on the other hand, is often interpreted to support the idea that lives show considerable plasticity, and that early experience need not be determinative of later abilities or predilections. In rejecting the dichotomy, we also reject the associated dichotomy regarding the importance of infancy: that infancy is either an absolutely crucial or a basically irrelevant period of life. Instead, by focusing attention on the telling of thickly written developmental stories, we support the idea that the delineation of any sensitive periods in development may be a very question-specific enterprise. Delineating the crucial age by which to correct amblyopia in order to ensure normal depth vision may not have the same answer as the crucial age by which to remove congenital cataracts, let alone the same answer as the crucial age by which to establish a deep emotional relationship.

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