INFANCY, *1*(2), 149–219

TARGET ARTICLE

Travel Broadens the Mind

Joseph J. Campos
Institute of Human Development
University of California–Berkeley

David I. Anderson
Department of Kinesiology
San Francisco State University
Institute of Human Development
University of California–Berkeley

Marianne A. Barbu-Roth, Edward M. Hubbard, Matthew J. Hertenstein, and David Witherington
Institute of Human Development
University of California–Berkeley

The onset of locomotion heralds one of the major life transitions in early development and involves a pervasive set of changes in perception, spatial cognition, and social and emotional development. Through a synthesis of published and hitherto unpublished findings, gathered from a number of converging research designs and methods, this article provides a comprehensive review and reanalysis of the consequences of self-produced locomotor experience. Specifically, we focus on the role of locomotor experience in changes in social and emotional development, referential gestural communication, wariness of heights, the perception of self-motion, distance perception, spatial search, and spatial coding strategies. Our analysis reveals new insights into the

Supplementary materials to this article are available on the World Wide Web at http://www.infancyarchives.com.

Requests for reprints should be sent to Joseph J. Campos, Institute of Human Development, University of California–Berkeley, Tolman Hall, Berkeley, CA 94720–1690. E-mail: jcampos@socrates.berkeley.edu

specific processes by which locomotor experience brings about psychological changes. We elaborate these processes and provide new predictions about previously unsuspected links between locomotor experience and psychological function. The research we describe is relevant to our broad understanding of the developmental process, particularly as it pertains to developmental transitions. Although acknowledging the role of genetically mediated developmental changes, our viewpoint is a transactional one in which a single acquisition, in this case the onset of locomotion, sets in motion a family of experiences and processes that in turn mobilize both broad-based and context-specific psychological reorganizations. We conclude that, in infancy, the onset of locomotor experience brings about widespread consequences, and after infancy, can be responsible for an enduring role in development by maintaining and updating existing skills.

When infants begin to locomote voluntarily, they undergo an extraordinary psychological reorganization. The onset of prone progression, especially hands-and-knees crawling, is followed by a staggering array of changes in perception, spatial cognition, and social and emotional development. This article delineates the major changes and consequences of self-produced locomotor experience that we identified using a variety of research designs and methods. The article updates previous reviews that we published (e.g., Berthenthal & Campos, 1990; Bertenthal, Campos, & Barrett, 1984; Campos, Kermoian, Witherington, Chen, & Dong, 1997), and includes the findings from many investigations that have been hitherto unpublished, or that we recently completed. Furthermore, in response to the challenge posed by some researchers (e.g., McKenzie, 1987), we go into greater depth than we have to date in elucidating the links between locomotor experience and psychological transitions.

The research we describe is relevant to our broad understanding of how development takes place. Most approaches to developmental origins and transitions are either monistic or domain specific. A monistic view, typically exemplified by stage theories, leads a person to expect broad psychological changes to result from a single organismic process. Usually, monistic views propose that development occurs synchronously across domains (Emde, Gaensbauer, & Harmon, 1976). Domain-specific approaches, by contrast, consider development as the accrual of quite specific changes in discrete domains, with little relation of one domain to the other, and with no necessary synchrony or sequence among the domains (Smith & Thelen, 1993).

We propose a hybrid of the monistic and the domain-specific approaches. We argue that a single, universal, developmental acquisition—the onset of locomotion—produces a family of experiences, with each member of the family being implicated in some psychological changes but not in others. In addition, we note that in some cases several processes coalesce, sometimes in apparent synchrony with each other, sometimes one preceding another in an orchestrated fashion, to gener-

ate a specific psychological change. So, even though a number of psychological phenomena are related to a single pacer or organizer (in this case, locomotor experience), each outcome is dissociable from the other. The outcomes need not be correlated very highly despite commonality of origin.

Thus, as we conceive it, locomotion is a setting event, a control parameter, and a mobilizer that changes the intrapsychic states of the infant, the social and nonsocial world around the infant, and the interaction of the infant with that world. In our view, locomotion is not by itself a causal agent. The developmental changes chronicled in this article are not a function of locomotion per se; rather, the changes stem from the experiences that are engendered by independent mobility.

IS LOCOMOTOR EXPERIENCE NECESSARY OR SUFFICIENT FOR PRODUCING PSYCHOLOGICAL CHANGES?

We believe that locomotor experience is a crucial agent of developmental change, but ironically, it might be neither necessary nor sufficient for bringing about these transitions. There are at least four reasons why locomotor experience might not be necessary for developmental change, and one reason for its insufficiency.

First of all, locomotor experience does not create new psychological skills ex nihilo. In virtually every domain we investigated, infants show some evidence of the perceptual, cognitive, or emotional characteristic in question before the onset of locomotion. Following Haith (1993), we call the existence of perceptual, cognitive, or emotional biases and precocities the principle of *partial accomplishment.* We refer to this principle many times in the course of this article. Although locomotor experience might not be responsible for the origins of a phenomenon, it can elevate some psychological skills to a much higher level. Such experiences thus are important for psychological advancement, but not necessarily for emergence.

Second, locomotor experience might not always be sufficient for producing a psychological skill because in a few cases infants can acquire the full-blown skill that ordinarily follows locomotor experience even prior to locomotion. For example, in our research we found that occasionally an infant will acquire wariness of heights prior to locomotor onset, although they usually do not. We call this state of affairs the principle of *precocious exposure.* This state of affairs is different from the principle of partial accomplishment. It is not a matter of locomotion improving an existing psychological skill; rather, it is a case of the causal processes usually produced by locomotor experience being recruited in nonlocomotor ways. Whether by serendipity or by design, the causal agents in locomotor experience can be brought about other than by locomotion, although they typically are not.

Third, we believe that human development shows the operation of alternative developmental pathways to the ones that usually bring about transition. This is the

well-known, though little studied, principle of *equipotentiality*. This principle differs from the precocious exposure insofar as equipotentiality reflects the production of a particular psychological outcome by a different process than that linked to locomotion. In precocious exposure, it is the same process. (An example of equipotentiality is the development of wariness of heights in prelocomotor infants because of a particularly painful fall instead of the more typical process involving the decoupling of visual and vestibular proprioceptive information that we describe later.) Equipotentiality has been implicated in the apparent normal development of Piagetian sensorimotor skills ordinarily thought to depend on manual and locomotor exploration in infants whose mothers had taken thalidomide in the 1960s (e.g., Decarie, 1969; Kopp & Shaperman, 1973). These children were apparently able to acquire functionally identical end-states by using their feet, heads, mouths, or in some cases orthopedic appliances to replace the locomotor and other motoric experiences they lacked.

Finally, in a few cases, locomotor experience might not be required to induce or facilitate a psychological skill, but can be necessary for updating the skill and preventing it from eventual loss from disuse. This is the principle of *maintenance by experience*. There has been remarkably little research with humans on this principle; we elaborate on its developmental significance in the response article later in this issue. Suffice it to say here that phenomena such as calibration of perceptual skills or attainment of psychological goals require a constant availability of locomotor experience or its surrogate to update the relation of persons to their environment. The need for locomotor experience thus can be indispensable throughout life.

There are also likely to be many instances in which locomotor experience might not be sufficient to bring about psychological changes. In some cases, the insufficiency of locomotor experience stems from the hierarchical integration and organization of development (Fischer & Biddell, 1998). That is, the process of development often involves integrating a number of component subskills into a higher order one that links together the previous dissociated skills. (An example of hierarchical development is the development of means–ends relations, wherein a skill such as lifting a cloth, and a second skill such as reaching for a toy, are coordinated and sequenced into a single complex act of uncovering and capturing a hidden toy.) The principle of hierarchical organization implies that if any crucial subskill has not yet developed, and if locomotor experience requires that subskill to mobilize a psychological reorganization, then locomotor experience will not result in a particular psychological transition. The locomotor experience will need to await other developments to effect a change. In short, hierarchical integration imposes constraints on developmental transitions; hence, a person should not expect precocious locomotor experience to bring about precocious psychological changes of the sort ordinarily seen when locomotion develops at normative ages. As with psychological maintenance and equipotentiality, there have been very few studies

on the effects of timing of a locomotor acquisition on psychological development (for an exception, see Biringen, Emde, Campos, & Appelbaum, 1995).

Are we minimizing the importance of locomotor experience as an agent of developmental change by arguing against the certainty of its causal role in infancy and later? We think not. Rather, we propose that the absence of necessity and sufficiency is probably the rule in most of human psychological and biological development. Indeed, that is a central tenet of systems approaches to development. Our argument for the importance of locomotor experience rests on evidence, which we are about to present, demonstrating that locomotor experience (a) is typically the agent of transition in many different psychological domains in most infants, and (b) has an extraordinarily widespread spectrum of consequences. The rest of this article is an attempt to substantiate these two propositions.

TWO CAVEATS ABOUT THE COURSE OF DEVELOPMENT

Before beginning our description of the findings linking locomotor experience to psychological development, two other important caveats are in order. First, locomotor experience should be expected to show neither a monotonic nor a linear relation with any psychological outcome. Because of the hierarchical nature of developmental change, development will often take place by spurts, rather than by slow accretions. If so, correlation coefficients might be misleading in describing or testing the relation between the duration of locomotor experience and psychological change (see Bertenthal & Campos, 1984, for a more detailed discussion of this point). Linear relations will be inadequate descriptors of these functional relations under at least two conditions. One occurs when development follows a course that is more like a step preceded and followed by a plateau (i.e., an ogive); the second, when intermediate states of developmental flux and disorganization bridge two stable states, one prior to locomotion, and another after locomotor experience. Failure to consider nonlinear developmental functions can account for many of the negative findings in the literature on locomotion and psychological change (e.g., Arterberry, Yonas, & Bensen, 1989; Rader, Bausano, & Richards, 1980; Scarr & Salapatek, 1970).

The second caveat draws us into the classic but still remarkably relevant issue of the role of genetics and experience in human development. The period of life surrounding the onset of locomotion appears to be one of the major life transitions in early development (Emde et al., 1976). As we have noted elsewhere (Bertenthal et al., 1984), there has been an implicit assumption that when broad-scale changes occur, maturation invariably must be posed as the underlying cause. Indeed, a number of the skills that we link to locomotor experience (e.g., search for hidden objects, secondary intersubjectivity, reactions to heights) have been said to be the

result of maturation. However, the converging research designs used to document this point corroborate that this life transition is not necessarily mediated by maturational factors (i.e., by the unfolding of a genetic blueprint for psychological changes), but instead, is intimately linked to experience. The studies on the consequences of self-produced locomotion (SPL) do not minimize the importance of genetically mediated changes; however, they do point, at the very least, to ecological and transactional sources of *coaction* (Gottlieb, 1991) between genes and early experiences. In sum, a major objective of this article is to illustrate in a major psychological transition in infancy the role of experience—a role that has been relatively underemphasized recently. However, nothing that we say in this article should be construed as an argument against intraorganismic biological contributions to development. It is merely that our methods are more suited to discovering experiential contributions to development, rather than endogenous ones.

CONVERGING RESEARCH OPERATIONS POINTING TO THE IMPORTANCE OF LOCOMOTOR EXPERIENCE

In earlier reviews of this work, we referred to some of the converging research operations by which one can infer the role of locomotor experience in psychological development. The objective of these converging operations is to determine whether locomotor experience plays a role as a concomitant or an antecedent of psychological changes. The simplest approach is to hold age constant and classify infants into those with and without locomotor experience. A second approach is the opposite of holding age constant—allowing age to vary along with locomotor experience. This approach, called the lag-sequential research design, results in classifying infants into a number of groups. For example, one group is early in crawling relative to locomotion norms for the population being studied; a second group is late in locomotion onset (also relative to population norms); and a third group acquires locomotion at the normative age. Infants are tested at the onset of locomotion and after selected amounts of locomotor experience, thereby permitting the assessment of the role of age, locomotor experience, and their interaction on the targeted psychological skill. The lag-sequential approach differs from the classic longitudinal design in oversampling early and late crawlers, so that the role of locomotor extremes might best be quantified without undue influence from the center of the normal distribution.

There are two other converging research operations that can help identify the role of locomotor experience. One of these involves the study of prelocomotor infants who have used wheeled carts or walkers that permit self-locomotion, often in a very skillful and goal-directed fashion. Higher levels of performance on psychological tests between these walker infants and matched prelocomotors who have

had no such walker experience strengthens conclusions about locomotor experience as an antecedent of psychological change. The other converging operation is the study of locomotor delay and what takes place psychologically upon the delayed acquisition of locomotor experience. The study of locomotor delay assesses whether infants who are normatively slow to locomote show corresponding psychological delays, followed by an elevation in function after the delayed acquisition of locomotion.

In this article, we instantiate the study of locomotor delays with two types of populations. One is in urban China, where for ecological and cultural reasons, infants show a 3.3-month delay in the onset of locomotion, relative to Bayley Scale norms (Bayley, 1969). The delay results from the constrained living arrangements in contemporary urban apartments. Infants in China are typically placed on a bed, surrounded by thick pillows to prevent falling. Moreover, the bed is often soft, like a featherbed, and does not provide enough resistance to the child's efforts to push up, resulting in delayed development of the musculature in the shoulders and upper trunk—musculature needed to support locomotion. The use of bulky clothing to provide warmth to the infant also might impair movement and muscular development. In addition, parents in China do not engage in activities that involve reciprocal innervation of the musculature on the sides of the trunk, such as tipping the infant first to one side, then to the other. Such reciprocal activity is also a prerequisite for locomotion. Furthermore, the Chinese parents are very concerned about the child's cleanliness and discourage crawling to prevent dirty hands.

The second population of infants we studied has a neurological basis for the locomotor delay. One such neurological problem is menygomyelocele or spina bifida. A neural tube defect, menygomyelocele results in a locomotor delay—the higher the lesion in the spinal cord, the later the age of onset of locomotion. If the defect is quite low, for example, at the sacral level, the spina bifida condition is typically not associated with severe cerebral involvement, although spina bifida increases its likelihood. Sacral lesions can bring about locomotor delays ranging from 4 to 7 months (Shurtleff, 1986). To minimize higher central nervous system confounds, we focused on infants with low, sacral, lesions.

These converging operations reflect our conceptual focus on the importance of early experience. However, we reiterate that biological and maturational factors are likely to be important as coactants in the developmental process. Research must therefore be designed to do justice to the concept of coaction of genes and environment. Consequently, at the end of this article, we present some of our preliminary ideas on how to conduct research that might reveal the separate and interactive contributions of endogenous, genetic factors along with experience in the transitions we describe.

In the subsequent sections, we point out the consequences of locomotor experience for (a) the child's social and emotional development, (b) the perception of

self-movement and its consequences, (c) distance perception, (d) the infant's manual search for hidden objects, such as in the A-not-B error with a delay, and (e) the infant's spatial coding strategies. In each section, we outline the specific experiences that locomotion generates and that, in turn, help to bring about the psychological changes seen in each specific domain. We suggest, where possible, new hypotheses about linkages between locomotor experience and psychological function. Next, we describe an experimental approach to the issue of whether locomotor experience is a cause or only an antecedent of the observed psychological changes. Finally, we note how other achievements that change the relation of the child to that child's social and physical world are also likely to lead to major psychological reorganizations.

SELF-PRODUCED LOCOMOTOR EXPERIENCE AND SOCIOEMOTIONAL DEVELOPMENT

Crawling as the "Psychological Birth of the Human Infant"

Many psychoanalytic theorists consider locomotion crucial for emotional development. Mahler, Pine, and Bergman (1975) went so far as to consider locomotion as the event that brings about the "psychological birth" of the human infant. By that they mean that locomotion breaks the symbiosis of infant with mother, creates autonomy and willfulness in the infant, and initiates a period of glee and a "love affair with the world." The onset of locomotion creates new challenges for the parents as well. One of these is the need to encourage exploration while discouraging the prohibitable. Another is to cope with the infant's new autonomy, which is welcome by some parents and regretted by others. We agree with Mahler et al. and differ from them in only one way: We propose that the origins of these changes in the infant, the parent, and the family system come from prone progression, and not, as they maintained, principally from upright locomotion.

Locomotion and social signaling. In addition to autonomy and willfulness, locomotor experience profoundly affects the infant's social cognition. When the child begins to crawl, there is a dramatic change in the type and source of social signaling that the child receives. Crawling increases the number of opportunities for the caregivers to communicate facially and vocally in the service of regulating the infant's explorations. Indeed, we speculated that crawling is the cradle of the social referencing phenomenon (Campos & Stenberg, 1981). It is principally after crawling that the child receives social signals that have a clear distal referent; prior to crawling there is little need for distal emotional communication. The importance of the origin of such distal communication for semantic comprehension and the "catching" of emotions cannot be underestimated (Moore, 1999).

Locomotion and attachment. The acquisition of SPL is a watershed in the formation of the attachment relationship. Bowlby (1969) spoke of locomotion marking the onset of the phase of discriminated attachment figures, as did Ainsworth and her colleagues (Ainsworth, Blehar, Waters, & Wall, 1978). Perhaps the most basic role of locomotion in attachment is in proximity seeking, which is the hallmark of the attachment relationship. Although proximity seeking might be attained through the indirect effects that social signaling can have on others, it is only through locomotion that the child can directly control distance from the attachment figure. Furthermore, the functions of the attachment relationship, to permit a secure base for exploration and a haven of safety in times of fear, require locomotion for their implementation.

Locomotion and motivation. If emotions reflect the fate of a person's goals (Lazarus, 1991), the onset of locomotion must markedly enrich the infant's emotional life. Crawling creates many new goals and enables the attainment and frustration of many others. Thus, crawling onset makes many familiar emotions much more prevalent, results in linking existing emotions to new objects (e.g., through the catching of emotions mentioned earlier), and creates the context for the emergence of new emotions (e.g., shame, pride, and other emotions that depend on distal social signaling).

Reorganizing the family system. Parents readily acknowledge that the onset of crawling brings about major social and emotional changes in the infant, the parents, and their interaction. Locomotion thus reorganizes the family system. The infant not only "gets into everything," but also makes happy the mother who strives for her baby's independence, saddens the mother who likes the prelocomotor infant's dependency, and imposes a demand on all parents to socialize the infant to explore what is safe and avoid what is dangerous. In this section, we review work on the reorganizations in the infant and the family following the onset of locomotion. We also describe a number of studies that show how locomotor experience is linked to the infant's growing sense of social understanding.

An Interview Study Linking Locomotor Experience and Socioemotional Development

In this section, we review work on the reorganizations in the infant and the family system following the onset of locomotion. We begin by describing an interview study that shows how mothers attribute to the infant a growing sense of internal responsibility, change their behavior toward the infant as a result of the infant's new attributions, and thus bring about changes in the infant's behaviors toward them. This interview includes data related to the role of locomotion in the development of

what Trevarthen (1993) called secondary intersubjectivity, and what others believe to be the origins of theory of mind (Moore & Dunham, 1995).

The interview study (Campos, Kermoian, & Zumbahlen, 1992) used a 2 × 2 design, crossing prelocomotor versus locomotor status of the infants with use of walker or not. The mothers were thus classified into one group if their infants were entirely prelocomotor, a second if their infants had at least 5 weeks of crawling experience, a third if the infants were crawling for 5 weeks and had at least 4 weeks of walker experience, and a fourth if the infants were prelocomotor and had at least 4 weeks' use of a walker. All infants were 8.5 months of age, and numbered 16 per group. Because there were few differences in the results of locomotor infants with and without walker experience, the data from these two groups were pooled. Its nature as an interview study constrains interpretation of the findings to parental perceptions and attributions. However, the study was designed to minimize the possibility of tapping into mothers' naive theory of locomotor consequences by including many questions on developmental changes in the infant besides those on locomotor experience.

Results related to changes in the infant. With reference to three major areas—emotional expression, attachment, and attentiveness to distal events—the study revealed a number of differences as a function of whether the mothers were reporting on prelocomotor or locomotor infants. In the emotional realm, the number of locomotor infants reported to have recently shown a large increase in anger was significantly greater than prelocomotors. Locomotor infants changed in terms of the frequency of angry responses to events and the manner by which they expressed anger. Mothers of locomotor infants reported an increase in the intensity of their infants' anger. As one mother stated, her infant was "showing the beginning of temper tantrums." These data are presented in Figure 1.

In the attachment realm, locomotor infants were reported more often to show increased, new, or intense forms of affection to the primary caregiver, a greater sensitivity to maternal departures and whereabouts, and increased checking back in social situations. Increased checking back to the mother and increased wariness of maternal departures accompanied a significant elevation in locomotor infants' attending to distal events.

Changes in the parent. Crawling produced changes in the mother as well, as indicated by parental reports summarized in Figure 2. Mothers of crawlers stated that they began to expect compliance from their infants; they felt that their infants were now responsible for their actions, and hence, they were expected to obey the mother. Mothers of locomotors also reported increasing their use of verbal prohibitions and mentioned how they used their voice predominantly as the means of conveying prohibition. Most strikingly, they reported a sharp increase in their expression of anger toward their infants, stating in many cases that it was the first time in

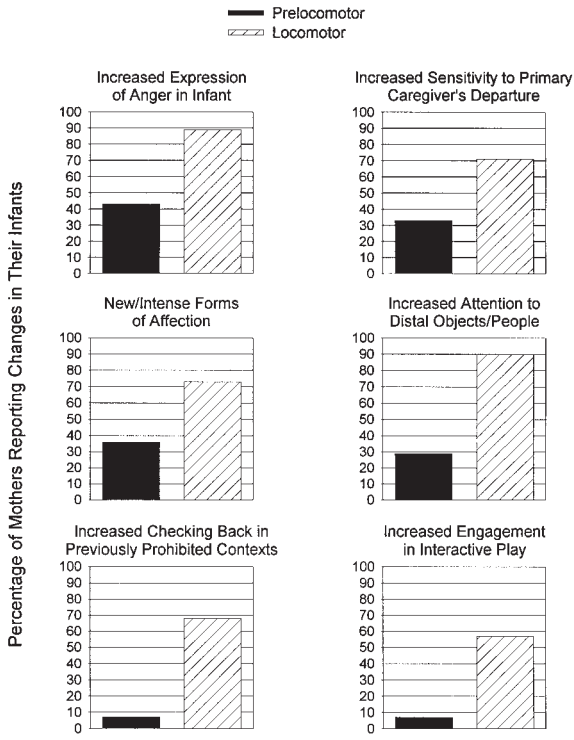

FIGURE 1 Reports by mothers of prelocomotor and locomotor infants of recent changes in their infants' emotional expression, attachment, and attentiveness to distal events. Adapted from "Socioemotional transformations in the family system following infant crawling onset" by J. J. Campos, R. Kermoian, & M. R. Zumbahlen. In N. Eisenberg & R. A. Fabes (Eds.), 1992, *Emotion and its regulation in early development* (pp. 25-40). San Francisco: Jossey-Bass. Copyright 1992 by Jossey-Bass. Adapted with permission.

their relationship that they had been angry toward the infant. In some instances, the expression of anger went so far as to lead to the use of physical punishment. Coincident with these increases in negative expressions, mothers of locomotor infants showed new and intense forms of affection toward their infants, manifested as increased frequency and intensity of hugging.

Changes reported in family interaction. This study portrayed the relationship between the parent and the locomotor infant as involving reciprocal changes in expression of anger and an apparent tug-of-war between infant willfulness and parental demands for compliance. Furthermore, the interview revealed some noteworthy changes in other interactive domains as well. One was the degree

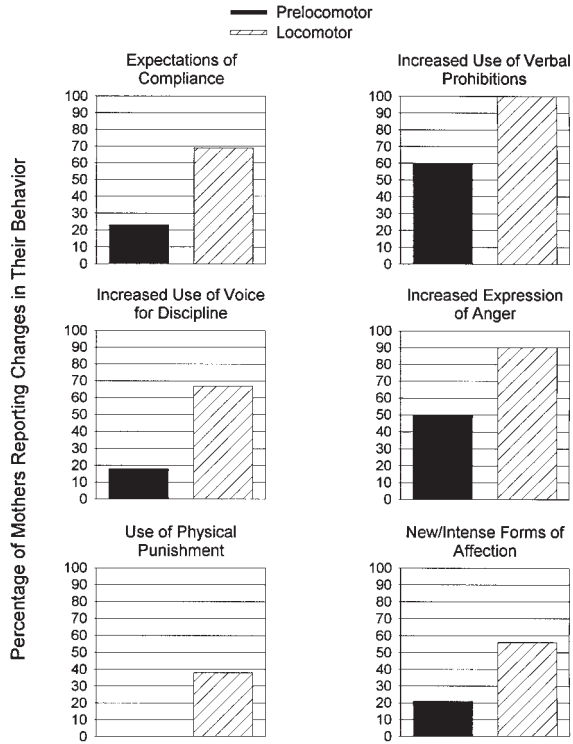

FIGURE 2 Reports by mothers of prelocomotor and locomotor infants of recent changes in their own (maternal) behaviors directed toward their infants. Adapted from "Socioemotional transformations in the family system following infant crawling onset" by J. J. Campos, R. Kermoian, & M. R. Zumbahlen. In N. Eisenberg & R. A. Fabes (Eds.), 1992, *Emotion and its regulation in early development* (pp. 25-40). San Francisco: Jossey-Bass. Copyright 1992 by Jossey-Bass. Adapted with permission.

of interactive play reported as a function of locomotor status (see Figure 2). Interactive play referred to games involving reciprocity on the part of the child, such as peek-a-boo. Maternal reports indicated that more locomotor infants initiated interactive games and showed more intense forms of positive affect including "glee" in these games.

The role of walker experience. Interestingly, in this study, few differences were found between infants who were prelocomotor but had experience moving about in walkers, when compared to prelocomotor infants with no walker experience. However, there were two noteworthy findings in which the mothers of prelocomotors with walkers reported behaviors in their infants that were more like

the reports of mothers of locomotor infants. Prelocomotors with walkers were reported to have shown increases in attention to distal objects and people, and increased checking back to the mother in previously prohibited contexts.

This lack of difference on most variables between prelocomotor infants with and without walker experience was not expected. We suspect that walker experience might not mimic crawling in ways significant for affecting social interaction. We propose several reasons for these negative findings. One is ecological. For instance, the tray surrounding the walker minimizes the number of objects the infant can inappropriately handle, reducing the need for the mother to use distal communication for emotional regulation. Furthermore, infants might use the walker more for its intrinsic "function pleasure" of locomoting, and much less for other purposes, such as playing with the stereo or electric outlets, that have more affective valence for the mother. Moreover, we believe that mothers can often use walkers as distractors or sources of entertainment for the baby; we suspect that they monitor the behavior of walker infants much less than they do that of a crawling infant. Nevertheless, the interview study proved to be one of the few instances in which walker experience did not yield findings similar to those for crawling infants.

Locomotor Experience and Socioemotional Development: Direct Observation

To provide confirmatory evidence on socioemotional changes in the family following crawling onset, Zumbahlen (1997) conducted for her dissertation a short-term longitudinal study directly observing mother–infant interaction prior to and following the onset of hands-and-knees locomotion. She observed 41 infants at 6 and 8 months. All 6-month-old infants were prelocomotor, and of the 8-month-olds, 18 had not begun hands-and-knees crawling, and 23 had been hands-and-knees crawling for an average of 5 weeks.

Zumbahlen (1997; Zumbahlen & Crawley, 1997) confirmed four major findings from the interview study. For example, she observed that the number of prohibitions increased following hands-and-knees crawling onset, and that these prohibitions took place most often in distal contexts. She also reported a sharp increase in the locomotor infant's expression of anger and also in the incidence of checking back when the mother initiated emotional communication with the infant.

Zumbahlen (1997) did not confirm the reported increase in the use of physical punishment by the parents of locomotor infants. Rather, she discovered that parents, to regulate the child's behavior toward prohibitable objects, distracted their children and moved the infant away from such contexts. Nevertheless, her study confirmed the general findings of the interview. The interested reader is referred to Zumbahlen for more details of this important study.

Locomotor Experience and the Origins of Referential Gestural Communication

There is a finding reported in this article that has a major bearing on the social and emotional development of the infant that is also very consistent across the transitions centering on locomotion. The finding has to do with changes with locomotor experience in the nature of the infant's attentiveness to distal events, illustrated in the interview study by the findings on checking back to the mother. These changes in attentiveness prove to be relevant to the ontogeny of referential gestural communication and "joint attention."

In the opening of Churcher and Scaife's (1982) review of literature on the phenomenon of joint attention, they used an illuminating analogy, citing a French proverb indicating that when the finger points at the moon, the idiot looks at the finger. The data and the rationale we discuss suggest that, on the whole, the prelocomotor infant is like the child in the French proverb, while the locomotor infant is more adult-like in following a referential gestural communication toward a distal target.

Why a link between locomotor experience and responsiveness to referential gestures? The interview and longitudinal study confirmed the observations of Mahler et al. (1975) about a sharp increase in checking back to the mother following the onset of prone progression. This pattern of checking back and forth is a component of the information-seeking aspect of social referencing (Campos & Stenberg, 1981), and as such, is relevant to understanding how values are imparted to the infant and how social regulation is effected by means of distal communications. It is through such emotional signaling that the mother can share meanings—affective and linguistic—with her infant. Thus, the pattern is important to investigate more formally (Corkum & Moore, 1998; Moore, 1999).

Consistent with the principle of partial accomplishments mentioned earlier, recent reviews (e.g., Moore, 1999) have noted that even prelocomotor infants have some capacity to respond to referential gestural communication. For instance, there appear to be three steps in the development of correct responsiveness to referential gestural communication (Moore, 1999). One step takes place well before locomotion onset—as early as 3 months—and is evident in successful responding of the infant to head and eye movements so long as the tester's head and the target of the communication are in the same visual field (D'Entremont, Hains, & Muir, 1997). There is a second level, beginning around 9 months, when the infant can respond to such communications when there is no target to the gestures of the experimenter. (Alternatively, in our view, the second level occurs when the gesturer is in one visual field, and the target of the gesture in another.) A final level, seen in the second year of life, involves correct localization of the target of referential communication even when the target is behind the infant.

We initiated a series of investigations on the second of these three levels and tested whether changes in referential gestural communication followed locomotor onset (Campos et al., 1997; Tao & Dong, 1997; Telzrow, 1990; Telzrow, Campos, Kermoian, & Bertenthal, 1999). These investigations involved an age-held-constant design, and the converging operations involving walker experience and locomotor delay in handicapped and Chinese infants. We initiated this line of research on the assumption, documented in the interview study, that crawling experience results in an increase in distal communication from a mother who is now typically at some distance from the infant and the referent of her utterance. More specifically, when the infant begins to locomote, the infant inevitably encounters prohibitable objects and contexts. As already noted previously, these encounters typically result in the parent using distal affective information to distract or inhibit the infant from the behavior. As the infant initially becomes exposed to this form of communication, the infant orients toward the parent. Orienting is the first phase in the development of the infant's attention to the mother's affective messages. Repeated often enough, such orienting to affective messages motivates the infant to determine the object of the mother's communication. Concern with the referent of the affective message is the second phase in the development of the gestural communication phenomenon. The second phase is further facilitated by the infant's new levels of attentiveness to distal displays, as well as new spatial understanding (e.g., to landmarks) made possible by distinct processes linked to locomotor experience. (The development of spatial attentiveness and understanding of landmarks are elaborated on in subsequent sections of this article. Suffice it here to note that the direction of the head and eyes, and that of the arm and pointing finger, constitute landmarks for localizing an object.) The outcome of these conjointly operating processes of distal attentiveness and understanding of spatial relations is the infant's growing understanding first of the general direction, and subsequently, the more specific target of the parent's head turn, gaze, or pointing gesture that invariably accompanies distal affective messages. Early locomotor experience seems to play a role in the first of these changes.

Following the gaze and point gesture: Age-held-constant study. The hypothesis that locomotor experience should facilitate the infant's following of the gaze or pointing gesture was investigated in a study of 8.5-month-old infants (Campos et al., 1997). There were three groups of 22 infants: infants crawling on their hands and knees for 6 weeks, prelocomotor infants, and prelocomotor infants with 40 or more hr of walker experience. The testing situation involved a 5-foot-square curtained area in which there were eight toys. Two were placed 45° to the infant's left, one 45° above the infant's eye level and one 45° below eye level. Two other toys were placed 45° to the infant's right, at homologous positions relative to the infant's eye level. Another two toys were placed 90° to the infant's left, one of which was again 45° above and one 45° below eye level. Finally, a seventh and eighth toy

were placed in homologous positions 90° to the right. Looking at one of the eight toys, a female experimenter drew the infant's attention and simultaneously uttered a statement, such as "Look over there," while turning her head and eyes, and using an across-the-body pointing gesture. In her gesture, the finger of the pointing hand did not extend beyond the periphery of her body. The dependent variables were whether the infant looked to the same side as the experimenter, toward the experimenter's face, or toward the opposite side of the room from where the experimenter looked in the 3 sec following the experimenter's statement. A contrast between looking to the same side as the experimenter and to the opposite side is widely considered to be the minimal prerequisite for demonstrating referential gestural communication. Without such a comparison, following the point or gaze to the same side as the experimenter looked might be a spurious "pseudo-following" response (Moore, 1999).

The results of the study are presented in Figure 3 (taken from Campos et al., 1997). Both locomotor and prelocomotor infants with walker experience looked to the correct side on significantly more trials than did the totally prelocomotor infants. Each of the two groups with locomotor experience also looked significantly more often to the correct side than to the opposite side of the room; the prelocomotor infants did not look to the correct side more than to the incorrect. In sum, the prelocomotor infants behaved like the impaired child in the French

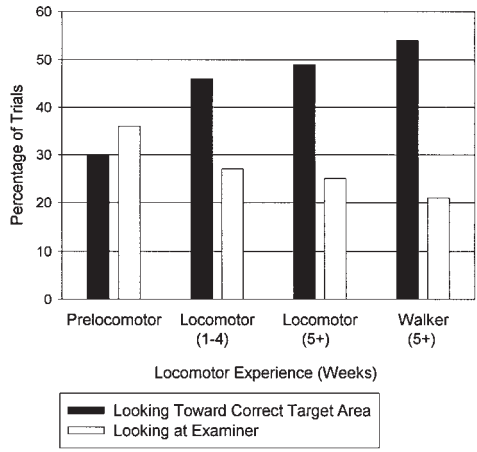

FIGURE 3 Following of a gaze and pointing gesture as a function of locomotor experience in 8.5-month-old infants. Adapted from "Activity, attention, and developmental transitions in infancy" by J. J. Campos, R. Kermoian, D. Witherington, H. Chen, & Q. Dong. In P. J. Lang & R. F. Simons (Eds.), 1997, *Attention and orienting: Sensory and motivational processes* (pp. 393–415). Mahwah, NJ: Lawrence Erlbaum Associates, Inc. Copyright 1997 by Lawrence Erlbaum Associates, Inc. Adapted with permission.

proverb, whereas infants with locomotor experience looked at least in the general direction of the moon in the metaphor. This study thus confirmed two points: (a) There is a developmental shift in referential gestural communication between 8 and 10 months, as Moore proposed; and (b) locomotor experience is implicated in the shift.

Two qualifications of the findings of this study need to be mentioned. First, the infants did not look to the correct target (the specific toy that the experimenter was looking at), but rather at the region in which the target was embedded. Second, the findings, although statistically significant, were not robust. It is clear that the phenomenon of joint attention, although affected by locomotor experience, awaits further developments.

Following the gaze and point: Infants with spina bifida. The findings of this study were confirmed in a study of infants with menygomyelocele (reported in Telzrow, 1990; Telzrow et al., 1999; Telzrow, Campos, Shepherd, Bertenthal, & Atwater, 1987). The study used the same paradigm as did the study just described (Campos et al., 1997). The infants in this study were recruited at approximately 5 months and were tested longitudinally every month for the period of the locomotor delay, and for 2 months after the delayed onset of locomotion. Locomotion occurred at 10.5, 11.5, 10.5, 8.5, 10.5, 13.5, and 10.5 months for infants 1 through 7 respectively. Locomotion was defined as intentional prone progression of 4 feet within 2 min. The group data are presented in Figure 4.

As is evident in the figure, prior to the delayed onset of locomotion, the spina bifida infants tended to look at the experimenter's face, and not toward the general region of the head turn, point, and gaze. However, upon the delayed acquisition of locomotion, the tendency to look at the experimenter's face dropped precipitously and the tendency to look in the general direction of the gaze and point increased significantly. (The numbers in this figure do not total to 100% because infants were also scored as doing nothing, or looking around at their bodies, etc.) In this study, 5 of the 7 infants showed the tendency to look in the general direction of the gaze or point; the 2 who did not show the shift toward rudimentary joint attention continued to look at the experimenter's face. The 2 infants who responded to the correct side even before locomotor onset might have been showing pseudo-following. Alternatively, they might be examples of the principle of precocious exposure we mentioned at the opening of this article (if their parents engaged in training the infants in referential gestural communication well before locomotion). Nevertheless, despite these two exceptions, a highly significant effect of delayed locomotor experience was found in this study.

Following the gaze: Locomotor delay in Chinese infants. The same paradigm used in the study cited in Campos et al. (1997) was also used in a cross-sectional study conducted in Beijing on 90 Chinese infants ranging in age

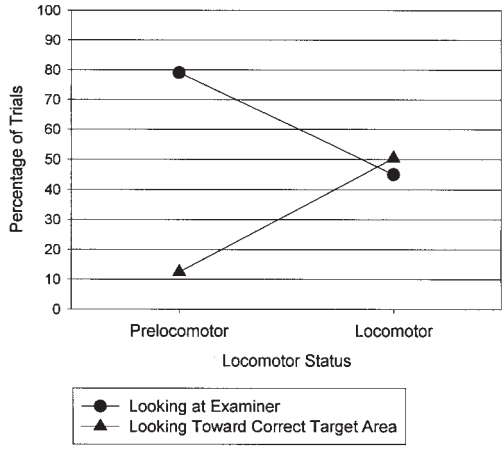

FIGURE 4 Following the gaze and point gesture in infants with spina bifida (data from Telzrow et al., 1999).

from 8 to 11 months (Tao & Dong, 1997). There were two major differences from the prior work. One was that in China, only the experimenter's gaze was used to refer to the target; the across-the-body point gesture was omitted in the study. The second was that in China only 8 trials were used, not 16. Despite the differences in procedure, the findings from China were similar to those obtained in the United States. Regardless of the age when the infants began to crawl (which in this study averaged 9.5 months), infants crawling on hands and knees for 5 weeks or more significantly outperformed precrawlers. The mean number of trials to follow the head turn and gaze to the correct side was 3.55 trials out of 8 for crawlers, compared to only 1.50 for prelocomotors—a significant difference. Infants crawling for 5 weeks or more also significantly outperformed infants crawling for 3 weeks or less (who searched in the correct direction on 1.54 trials). The Chinese infants rarely looked to the side opposite the experimenter's head turn and gaze. An analysis of covariance (ANCOVA) revealed a significant effect ($p < .03$) of crawling experience when age was statistically controlled.

A second investigation was conducted in China on following the gaze gesture of a female experimenter (Tao & Dong, 1997). The purpose of this study was to contrast the performance of two groups of locomoting infants of the same age. One group was constrained to the parent's bed (and thus had very limited experience with locomotion). The second group lived in apartments that permitted the infants to locomote on the floor; these infants were presumed to have more locomotor experience than the first group of infants. This study revealed a statistically significant difference ($p < .02$) between the two groups in following the gaze gesture, with floor crawlers

searching to the correct side on 6.3 trials, and those confined to the bed searching only on 4.1 trials. As in the earlier study, Chinese infants rarely looked in the direction opposite to the direction of the experimenter's head turn and gaze.

Taken as a whole, these findings consistently implicate locomotor experience in the development of referential gestural communication. Similar findings were obtained regardless of whether the investigation dealt with infants who crawl at normative ages, infants with spinal lesions, or infants delayed in locomotion onset because of cultural and ecological factors. In every study, hands-and-knees crawling infants with approximately 5 weeks of locomotor experience responded appropriately to referential gestural communication, and did so whether the gesture involved head turn, gazing, and pointing, or the head turn and gaze alone. We thus conclude that locomotor experience greatly facilitates the development of the child's social cognition and lays the basis for the future development of skills crucial for social referencing, emotional development, and language acquisition. Furthermore, because the understanding of referential gestural communication is a necessary component of "secondary intersubjectivity" (i.e., a two-person communication about a third event), we propose that the development of secondary intersubjectivity can depend at least partly on experience; explanations solely emphasizing "maturation" (Trevarthen, 1993) are likely incomplete.

Overview of Findings on Socioemotional Development

In this section, we described perhaps the broadest set of changes in infants following the onset of locomotion. Infants become more willful, more autonomous, more prone to anger and glee, more sensitive to maternal separations, more intense in their display of attachment behaviors, more likely to encounter the mother's wrath, more prone to begin social referencing, and more likely to initiate interactive games and processes. In addition, infants with locomotor experience perform better on a task assessing the tendency to follow referential gestural communications. Finally, because changes in the infant accompany changes in the family system, it is clear that the development of crawling is a crucial milestone for all family members. We now turn to a discussion and an explanation of a different emotional change in the child following locomotor onset.

SELF-MOTION PERCEPTION, SELF-PRODUCED LOCOMOTOR EXPERIENCE, AND WHY INFANTS COME TO FEAR HEIGHTS

In this section we consider the development of two perceptual abilities whose relation to self-produced locomotor experience appears to be particularly ro-

bust—wariness of heights and postural responsiveness to peripheral optic flow. Although most psychologists would agree that the latter ability falls clearly within the perceptual domain, many would argue that wariness of heights constitutes an emotional reaction rather than a perceptual phenomenon (Rader et al., 1980; Walk, Shepherd, & Miller, 1988). We do not make such a hard-and-fast distinction between perception and emotion; in fact, we argue that wariness of heights is brought about by a very specific, but hardly extraordinary discrepancy among visual, vestibular, and somatosensory information when a drop-off is encountered. The discrepancy also appears to be related to an individual's responsiveness to peripheral optic flow and, hence, wariness of heights is very much rooted in the perceptual domain. We elaborate on this argument subsequently.

As independent mobility emerges and develops, infants discover many new facts about themselves and their environment. These discoveries include what new information might be picked up from the environment; what information in the environment is relevant to the control of locomotion; and what objects, places, and events have consequences for a mobile organism. It should not be surprising, then, that the development of control over locomotion constrains perceptual development (the development of information pickup) just as perceptual development constrains the ability to control locomotion. Such interdependence between perception and action, referred to as *perception–action coupling*, and its implications for understanding human development, have recently captured the interest of psychologists (e.g., Bertenthal & Clifton, 1998; Bertenthal, Rose, & Bai, 1997; Reed, 1982; Schmuckler, 1993; von Hofsten, 1989).

The Development of Height Avoidance in Kittens

Locomotion is an excellent phenomenon for studying the ontogeny of perception–action coupling, as demonstrated by the now-classic kitten studies initiated by Held and Hein (1963). In a yoked-control design, two groups of dark-reared kittens were exposed in dyads to the same pattern and amount of visual stimuli during locomotion. One kitten roamed freely (though in a circular trajectory) in self-directed locomotion, while the second kitten was passively yoked to and moved about by the first kitten. The results of the study indicated that only those kittens with active locomotor experience developed avoidance of heights (Held & Hein, 1963). Conversely, once the kittens previously deprived of locomotor experience were allowed to locomote freely, height avoidance became evident within 24 hr. In sum, specific experiences provided by active SPL allowed the kitten to respond in a new, more developmentally advanced manner to environmental stimuli such as a drop-off. These findings were confirmed and extended in a subsequent study by Hein, Held, and Gower (1970).

Locomotor Experience and the Development of Wariness of Heights in the Human Infant

The findings by Held and Hein (1963) generalize to the human infant. In a variety of studies using the age-held-constant design, including walker manipulation, the study of motorically delayed infants, and lag-sequential longitudinal investigations, Campos, Bertenthal, and Kermoian (1992) documented that the role of experience is indeed crucial in mediating the development of wariness of heights. Using heart rate as an index of wariness of heights—an index that can be used with either prelocomotor or locomotor infants—Campos, Bertenthal, and Kermoian (1992) reported cardiac accelerations in infants lowered toward the deep side of a visual cliff, so long as the infants had experience crawling or controlling a walker. On the other hand, prelocomotor infants without any walker experience did not show any significant heart rate change. In a second study described in their article, Campos et al. tested infants who started to crawl at a relatively early age (6.5 months), at a normative age (7.5 months), and at a relatively late age (8.5 months). The dependent variable in this study was not heart rate, but rather the difference in the latency to cross to the mother when she called the infant to cross to her from across either the deep or the shallow side of the visual cliff. In all three groups, infants were tested after either 11 or 41 days of locomotor experience. The findings revealed that it was crawling experience and not age of locomotion onset that was associated with hesitation to crawl onto the deep side of a visual cliff. At no age or testing time was any hesitation observed in crawling onto the shallow side of the cliff when the mother called the infant to cross to her in that situation. These studies replicated and extended the findings from a previous longitudinal study (Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978) that showed after only a few weeks of locomotor experience infants began to avoid crossing the deep side of the visual cliff to reach their mothers. Taken together, these studies support the notion that the onset of wariness of heights develops as a result of the specific experiences engendered by SPL, rather than visual experiences in general.

The Concept of Optic Flow

Although the onset of wariness of heights was one of the earliest developmental changes to be linked to experience with SPL, the development of postural responsiveness to peripheral optic flow is one of the most recent. J. J. Gibson (1966, 1979) first introduced the concept of optic flow (i.e., the continuously changing ambient optic array produced by a continuously moving point of observation) in his discussion of the visual information available for the control of action. Gibson suggested that vision serves three major functions in locomotion to a destination. First, it allows an animal to steer an appropriate course such that obstacles are avoided and

the most economical route is taken. Second, vision provides information specifying whether a surface can be traversed. Not surprisingly, there is evidence that prelocomotor and locomotor infants differ in the properties of surfaces to which they attend (Schmuckler, 1993). Finally, vision provides an essential source of information for the maintenance of postural stability. This latter function is perhaps the least obvious of the three because the vestibular and somatosensory systems have traditionally been imbued with the role of providing information for postural control. However, there is considerable evidence that postural compensations can be induced in adults and children, if they are exposed to simulated optic flow in a "moving room," despite the fact that vestibular and somatosensory information specify postural stability (Bertenthal & Bai, 1989; Lee & Aronson, 1974; Lee & Lishman, 1975; Stoffregen, 1985).

The moving room is a large enclosure, open at one end, that is suspended just above the floor. Usually, the walls are lined with some type of patterned (striped, polka-dotted) material, and lights positioned on the side walls illuminate from the room within. Lee and Aronson (1974) were the first to show that infants as young as 13 months, who were just learning to stand, would sway and fall in a directionally appropriate manner when the room was moved back and forward along the line of sight. In other words, the infants took the movement of the surrounding environment as an indication that they were moving and attempted to compensate for what was only an illusion of movement (see Figure 5). Butterworth and Hicks (1977) subsequently provided evidence that standing was not a prerequisite for responsiveness to optic flow, as infants who could not yet stand showed similar postural compensations when tested in the moving room in a seated position. Subsequent research has shown that the visual control of posture is specific to the geometric structure of the optic flow in concert with the region on the retina that is stimulated (Bertenthal & Bai, 1989; Dichgans & Brandt, 1974; Stoffregen, 1985, 1986), and possibly to the magnitude of the retinal area stimulated (Crowell & Banks, 1993).

When the eyes look in the direction of movement, the central regions of the retina are exposed to a melon-shaped family of curves that radiate out in an expanding starburst pattern from the point where the mover is heading (illustrated in Figure 6). This type of pattern has been referred to as *radial flow* (J. J. Gibson, 1979). In contrast, at the periphery (the edges of the visual field), the lines of flow are nearly parallel to the line of movement, having a lamellar structure (Cutting, 1986) similar to the lines of longitude at the equator of a globe (also illustrated in Figure 6). When adults and children face the front wall of the moving room, they show much greater postural responsiveness to peripheral lamellar flow caused by movements of the side walls alone than by central radial flow caused by movements of the front wall alone (Stoffregen, 1985, 1986; Stoffregen, Schmuckler, & Gibson, 1987). However, there appears to be a developmental shift in responsiveness to spatially delimited portions of the optic flow between 5 and 9 months of age (Bertenthal & Bai, 1989).

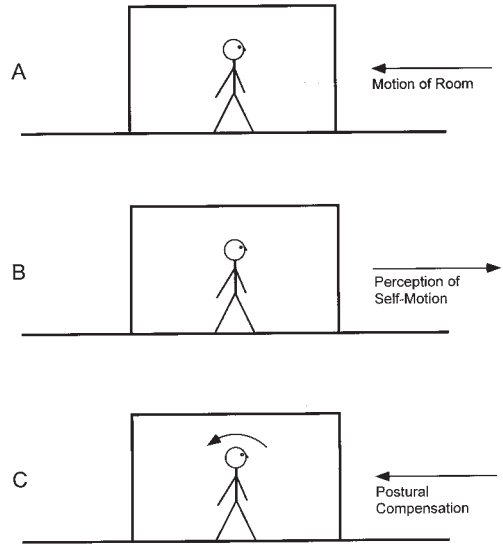

FIGURE 5 Demonstration of illusion of self-movement and postural compensation in a moving room. When the side walls of the room move from right to left (A), the observer perceives motion of the self in the direction opposite to side wall movement (B), and compensates for the perceived but illusory self-movement by adjusting the body in the same direction as side wall movement (C).

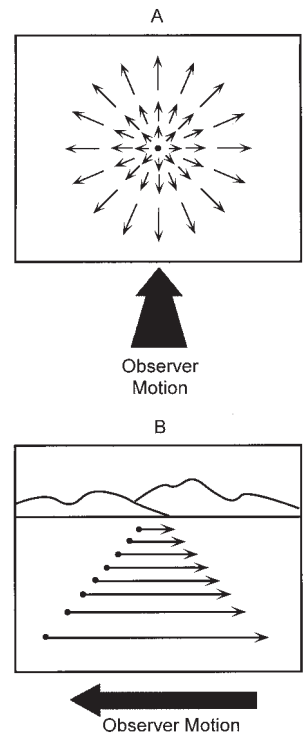

FIGURE 6 Patterns of optic flow. Radial optic flow presented to the central retina (A) and lamellar optic flow presented to the retinal periphery (B) when the head is aligned in the direction of forward motion.

Locomotor Experience and the Development of Postural Responsiveness to Peripheral Optic Flow

Using an enclosure that permitted independent movement of the front and side walls, Bertenthal and Bai (1989) exposed 5-, 7-, and 9-month-old infants to global optic flow (whole-room motion), central flow (front-wall motion only), and peripheral flow (side-wall motion only). Although 5-month-olds showed no systematic postural compensation to any of the room movement conditions, both 7- and 9-month-olds compensated in a directionally appropriate manner to whole-room movement. Most important, 9-month-olds, but not 7-month-olds, responded with systematic postural compensations to side wall movements, suggesting a developmental trend between 7 and 9 months in the ability to use peripheral optic flow for postural control. Not surprisingly, Bertenthal and Bai suggested that SPL experience might play an important role in this perceptual shift; a suggestion that was subsequently tested in an experiment by Higgins, Campos, and Kermoian (1996).

Using the same type of moving-room apparatus as Bertenthal and Bai (1989) and a refined technique that permitted calculation of the correlation between infant sway and wall movements, Higgins et al. (1996) reported that 8.5-month-old infants without locomotor experience showed minimal postural compensation to peripheral optic flow. In contrast, 8.5-month-old infants with hands-and-knees crawling experience or walker experience showed significantly higher degrees of postural compensation to peripheral flow. The differences between the three groups of infants can be seen clearly in Figure 7. Because infants in all three groups showed postural compensation to testing conditions other than those involving peripheral optic flow, Higgins et al. ruled out the possibility that prelocomotor infants were incapable of postural compensation at all. The relative unresponsiveness of prelocomotor infants in the moving room was specific to peripheral, lamellar flow conditions—namely, those conditions that typically and maximally inform the visual system of self-motion.

The Link Between Peripheral Optic Flow and Wariness of Heights

There is preliminary evidence that the developmental shift in infants' responsiveness to peripheral optic flow is related to the emergence of wariness of heights. Witherington, Campos, and Kermoian (1995) explicitly tested this relation in an experiment in which infants were tested in both the moving-room apparatus and the visual cliff. Twenty-two 8.5-month-olds with varying amounts of hands-and-knees crawling experience were exposed to side-wall movement in the moving room to assess the degree of coupling (i.e., correlation) between their body sway and the

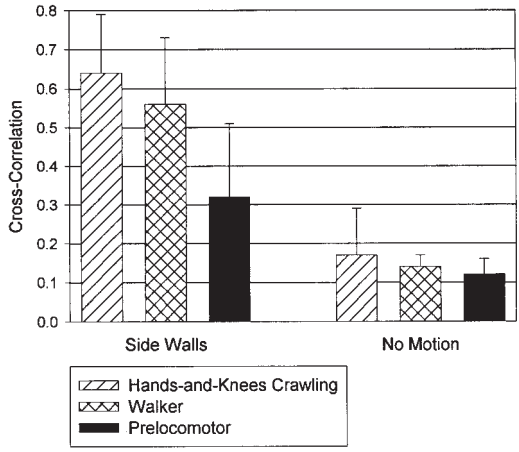

FIGURE 7 Responsiveness to side-wall motion and no motion in the moving room as a function of locomotor status. Adapted from "Effect of self-produced locomotion on infant postural compensation to optic flow" by C. I. Higgins, J. J. Campos, & R. Kermoian, 1996, *Developmental Psychology, 32*, 836–841. Copyright 1996 by the American Psychological Association. Adapted with permission.

movement of the walls. In addition, the infants were tested to determine their latency to move off the centerboard of the visual cliff and across the deep or shallow side toward their mother. A latency score was devised by subtracting shallow-side trials from deep-side trials such that a high latency reflected behavioral avoidance of the deep side but not the shallow side of the cliff. The most important result was that postural response to peripheral optic flow correlated positively and significantly with behavioral avoidance on the deep side of the visual cliff ($r = .58$), implicating the development of responsiveness to peripheral optic flow as a mediator of the emergence of wariness of heights. This relation is not trivial and subsequently we address its implications in more detail.

So far, we have provided evidence that locomotor experience brings about changes in postural responsiveness to peripheral optic flow, which in turn leads to changes in reactions to heights. Little has been said about how or why locomotion engenders such changes. Specifically, by what process(es) does self-produced locomotor experience foster these important perceptual changes? As we have already implicated responsiveness to peripheral optic flow in the emergence of wariness of heights, we begin by suggesting the means by which locomotor experience facilitates the infant's ability to attend to and use specific portions of the optic array for the various functions involved in locomotion to a destination. We then return to the specific mechanism by which wariness of heights can emerge.

How Does Locomotor Experience Facilitate Responsiveness to Peripheral Optic Flow?

Relative to maintaining stability in one place, the task of transporting the body from place to place is quite demanding on attention. Recall that J. J. Gibson (1979) suggested three major functions for vision during locomotion to a destination: steering, detection of surface traversability, and maintenance of postural stability over a dynamically changing base of support. These functions highlight the number of visual informational sources that must be processed concurrently as an infant moves through the environment. However, locomotion can be accomplished efficiently if the various sources of information are partitioned to those areas of the retina specialized to detect them. For example, the center of the retina is thought to be specialized to detect object properties and object motion (e.g., Leibowitz & Post, 1984), whereas, as is obvious from the preceding discussion, the retinal periphery is thought to be specialized to detect self-motion. Hence, a moving observer might maintain heading and steer an appropriate course using central radial flow and concurrently maintain postural stability by attending to lamellar flow presented to the retinal periphery. It is highly likely that the ability to differentiate the central radial optic flow and peripheral optic flow is learned during the acquisition of locomotor skill (Gibson & Schmuckler, 1989; Schmuckler, 1993). In other words, locomotion compels the infant to differentiate central and peripheral optic flow for the various functions involved in moving from place to place, if those functions are to be performed effectively and efficiently.

The foregoing argument does not imply that infants are insensitive to peripheral optic flow prior to the acquisition of locomotor skill; indeed, consistent with the principle of partial accomplishment mentioned earlier, Jouen (1988, 1990) elegantly showed that infants as young as 3 days of age show sensitivity to peripheral optic flow. Rather, we suggest, as have others (Bertenthal, 1990; J. J. Gibson, 1966; Jouen & Gapenne, 1995), that locomotor experience plays a role in the subsequent development of visual–postural coupling. Stated otherwise, locomotion brings about a marked shift in the utilization of spatially delimited portions of optic flow for controlling posture. Through a process of "optimization of attention" (E. J. Gibson, 1969), infants differentiate and fine-tune perceptual control of action during the actual practice of locomotion. Such fine-tuning or refinement of perception occurs to a degree hitherto unnecessary until the ability to locomote emerges. Furthermore, it is likely that the mapping between vision and posture that results from crawling experience will need to be remapped as the infant acquires new motor skills such as standing and walking (Adolph, Vereijken, & Denny, 1998; Bertenthal et al., 1997; Goodale, 1988; Milner & Goodale, 1995). In fact, remapping is likely to occur with the acquisition of every new motor skill in a continuously coevolving perception–action cycle.

Does Responsiveness to Peripheral Optic Flow Play a Role in Wariness of Heights?

Returning now to the role of locomotor experience in the emergence of wariness of heights, we suggest that the ability to use peripheral optic flow for postural control is a prerequisite for showing a fearful reaction on the visual cliff. This hypothesis hinges on the different relations among visual, vestibular, and somatosensory information to which an infant is exposed during both active and passive locomotion. When infants move toward a destination, they will generally look in the direction of motion so as to steer appropriately and keep the target of locomotion in view (e.g., Higgins et al., 1996). As such, infants who actively locomote will receive the typical optic flow patterns described previously: radial flow projected to the center of the retina and lamellar flow projected to the periphery of the retina. In addition, there will be congruence among visual, vestibular, and somatosensory feedback specifying the angular acceleration of the body and head in the direction of locomotion. Thus, infants who actively locomote will increasingly experience a strong degree of correlation among patterns of visual, vestibular, and somatosensory information. In contrast, nothing demands that passively moved infants (in strollers, cars, or parents' arms) direct their attention toward the direction of motion. In many cases, passively moved infants face in a direction opposite to the direction of motion and quite often peripheral optic flow is at least partially blocked as the infant is moved. As a result, visual input received during passive transport can be very different from input received by the vestibular and somatosensory systems. In other words, correspondence among visual, vestibular, and somatosensory information will be relatively low in the prelocomotor infant, and in contrast to actively locomoting infants, it is unlikely that any consistent expectations will develop as to the typical pattern of relations among them.

When locomotor infants confront a drop-off, or depth at an edge, their expectation of correlated visual, vestibular, and somatosensory information will be violated. When approaching the edge, the vestibular and somatosensory systems will specify motion, but the visual system will specify relative stasis, because visual contours at the site of the drop-off are too distant to provide much in the way of proprioceptive information about self-motion. The key to understanding this violation is that the rate of angular displacement of optical texture on the retina, which specifies visually perceived acceleration, is related to distance (Bertenthal & Campos, 1990; Brandt, Bles, Arnold, & Kapteyn, 1979). Remember also, that it is the lamellar flow projected to the retinal periphery that efficaciously specifies self-motion. The fact that infants who show greater postural response to peripheral optic flow also display more avoidance on the deep side of the visual cliff (Witherington et al., 1995) provides compelling evidence that the violation of expectancy among patterns of visual, vestibular, and somatosensory feedback is, at least in part, responsible for locomotor infants' fearful reactions on the visual cliff.

Uncorrelated feedback is not only responsible for postural instability but also for a range of physiological reactions including fear (Bertenthal & Campos, 1990; Guedry, 1974; Mayne, 1974).

In summary, we have provided evidence that the development of wariness of heights and postural responsiveness to peripheral optic flow are related to locomotor experience. Furthermore, we argued that these two phenomena are related to each other in that responsiveness to peripheral optic flow is considered a prerequisite to fearful reactions on the visual cliff. The former developmental change is thought to result from the increasing need to discriminate spatially delimited portions of the optic flow field if the important subtasks involved in locomoting to a destination are to be controlled effectively and efficiently. The latter change is thought to result from a violation in the expectation of correlated input from the visual, vestibular, and somatosensory systems when a drop-off is encountered. It is important to point out here that the expectation of correspondence among visual, vestibular, and somatosensory information is a direct consequence of locomotor experience. The arguments we presented here highlight the mutual interdependence between perception and action in the developmental process.

THE ROLE OF LOCOMOTOR EXPERIENCE IN THE PERCEPTION OF DISTANCE

In this section, we discuss the role of self-produced locomotor experience in the development of distance perception—the ability to gauge veridically how far an object is from the perceiver. The problem of distance perception is a classic issue that dates back at least to Berkeley (1709). At one time it was believed that information provided by vision about distance is too impoverished to allow for veridical perception of how near or how far an object is, let alone to direct spatially appropriate behavior. The motoric factors of accommodation (the thickening and thinning of the lens of the eye in response to image blur), convergence (the extent to which the two eyes are turned inward to fixate an object), reaching, and locomotion were deemed critical in providing information about distance that the visual system failed to provide by itself.

Following Berkeley (1709), Piaget (1954) described how the infant, after coordinating vision with reaching, constructed the perception of planes of depth, but only within the zone of reach and a little beyond (what Piaget called "near space"[1]). Beyond this range, according to Piaget, the world looks to the

[1]Johansson (1973) defined near space in adults to be less than 2 m. This definition is relevant later when we discuss the results of McKenzie, Tootell, and Day (1980). It seems that near space, in this case, is defined by the limits of sensitivity to the two sources of absolute information mentioned before, accommodation and convergence, which are effective in adults to about 2 m (6–8 ft).

prelocomotor child as flat as the night sky does to an adult—a plane in which the relatively close moon, the more distant planets, and the even more distant stars appear equally far from the perceiver. Slowly, locomotor experience provides the information to disambiguate "far space," and the infant can thus estimate the sizes and distances of objects veridically. Such motoric enrichment of visual information involves scaling visual information in terms of motoric units. Such scaling is called *calibration.* Thus, the objective distance of a toy from a baby is calibrated in terms of such variables as the length of a reach required or the number of strides that must be taken to get to it (Kaufman, 1974).

The impoverished vision hypothesis also predicts that size constancy, which is related to accurate distance perception (Holway & Boring, 1941; Rock, 1977), will require calibration. Until such calibration takes place by motoric enrichment of visual information, according to this hypothesis, an object receding from a prelocomotor infant must create an ambiguous percept. For example, without calibrating distance, the infant cannot tell whether the departing mother is shrinking or maintaining the same size while moving farther away. Although infants will possess size constancy in near space once reaching and vision are coordinated, they will lack it in space well beyond reach. Similar considerations apply to shape constancy. Specifically, the perception of any object will show a developmental trend ranging from absence of any constancy prior to reaching, to presence of shape constancy in near space, then to elaboration of shape constancy at ever greater distances subsequent to the infant's expanding locomotor experiences, and ultimately ending with the intervention of more cognitive triangulations permitting distance to be calculated precisely.

The classic view represented by Berkeley (1709) and Piaget (1954) is now discredited. For example, J. J. Gibson (1979) and others have claimed that the visual system, far from being impoverished, has all the information required for veridical perception. Although Gibson's view is not universally accepted (e.g., Palmer, 1999; Rock, 1997), he and his followers have uncovered numerous previously unexamined sources of information available for distance perception. Furthermore, an impressive array of empirical studies documented that even the newborn has the ability—within limits—to perceive correctly the size and shape of objects despite variations in distance and slant (e.g., Slater, Mattock, & Brown, 1990; Slater & Morison, 1985). Because the newborn has little reaching, poor convergence and accommodation, and no locomotor ability, the neonate's visual system must be capable of sufficiently accurate distance information to mediate the level of correct size and shape perception assessed in these investigations.

Do these findings suggest that locomotor experience is not relevant to the development of distance perception? We have already alluded to a tendency for the infant to possess a skill in some measurable way prior to locomotion but to show a dramatic tuning of that skill upon the acquisition of locomotion. We saw this tendency to be the case for visual proprioception—evident, though weakly, in the

newborn, yet showing step-function increases following a few weeks of locomotor experience. This tuning and subsequent step-function improvement in a psychological skill might be even greater in infants' perception of distance for, as Banks (1988) noted, the first year of life is a period of dramatic ocular growth and neural migration, which requires continuous recalibration if the infant is to perceive the world veridically.

We argue that the perception of size and shape constancy, and more generally, the perception of distance, show similar developmental improvements following the acquisition of locomotion, despite the reports of rudimentary neonatal skills in these domains. Our prediction is based on the premise that the prelocomotor infant's visual system can detect the information for veridical distance perception only within a limited range. Beyond that range, the distance-specifying visual information either is unattended to, or might be beyond the powers of resolution of the prelocomotor infant's visual system. Locomotion thus can calibrate distance information after all, but only for distances relatively far from the infant, and not in the fashion Piaget expected. Rather than adding information to an impoverished visual system, locomotion can help to calibrate distance by drawing attention to previously undetected depth-specifying information.

Locomotor Experience and the Redeployment of Attention

Prior to the onset of locomotion, the child might not notice the information in the distal optic array. Motoric factors, especially locomotion, might thus have a role in what J. J. Gibson (1966) called the "education of attention" to information that resides in visual input, but is not initially used by the visual system. Locomotion can be a parameter in the development of veridical distance perception in large-scale spaces provided that locomotion helps direct attention to distal displays. Several studies have discovered precisely such a change in the deployment of attention. One suggestive result can be found in the Campos, Kermoian, and Zumbahlen (1992) interview study mentioned earlier. More mothers of locomotor infants reported that their infants attended to distant objects and events than did mothers of prelocomotor infants. Several other lines of research, which we now describe, directly addressed the issue of changes in attention to distant events and reported differences between prelocomotor and locomotor infants.

Locomotion and deployment of attention to a destination. As discussed in the previous section, Higgins (1994; Higgins et al., 1996) found that infants with locomotor experience directed their gaze almost exclusively in the direction of motion as they crawled toward a distal goal. Hence, locomotion lures attention to far space, especially to the location toward which the infant is moving. If distracted, infants will discontinue forward motion and assume a "side-sit" posture to examine the distraction. In

contrast, the passively moved prelocomotor infant is not engaging in goal-directed locomotion and so has no need to maintain a specific focus of attention. Higgins's observations thus provide preliminary evidence that locomotor infants and passively moved prelocomotor infants have different foci of attention during movement through the environment.

Locomotion and attention to far space. In addition to this differential focus on specific portions of far space as a function of goal-directed locomotion, locomotor infants demonstrate general changes in attentiveness to far space compared to prelocomotor infants (Freedman, 1992; Gustafson, 1984). In two experiments, Gustafson (1984) studied the social and exploratory behaviors of 20 prelocomotor infants. In the first experiment, infants between 6.5 and 10 months were tested for 10 min in a walker and 10 min out of a walker. Gustafson found that during the time that they were in the walker, infants spent significantly more time looking at far space, that is, at distant toys, people, and other features of the room. In the second experiment, Gustafson compared the behavior of the prelocomotor infants while in the walker with that of locomotor infants. She found no significant differences in the extent to which the walker infants and hands-and-knees crawlers looked to far space. Again, these findings indicate that there is a difference in the allocation of attention to space that is brought about by SPL.

Other research, conducted in our lab by Freedman (1992), further demonstrates that deployment of attention varies as a function of locomotor experience. Using an age-held-constant design, thirty 8.5-month-old infants were assigned to one of three groups of 10 each: prelocomotor, prelocomotor with walker experience, and hands-and-knees crawling. Infants in the hands-and-knees crawler group had at least 5 weeks of locomotor experience. Infants in the walker group had similar amounts of experience through use of a walker. The infants' task was to manipulate a canister in front of them that activated a display either in front of them and within reach, or two displays to the infants' side and beyond reach. One of the out-of-reach canisters was 5° to the right of midline, and the second was 60° from midline. Freedman obtained a number of noteworthy findings. For example, she found that prelocomotor infants were just as likely to look away to far space as locomotors, but they differed in what they focused on in far space. More specifically, she found that infants in the two groups with locomotor experience looked in the direction of objects in far space, whereas infants without locomotor experience when looking beyond reach tended to look at nothing in particular—at vacant parts of the room (see Figure 8). In addition, both hands-and-knees crawler and walker infants were more likely than prelocomotor infants to look toward far space while manipulating objects in near space. The results of the walker infants were not significantly different from those of the hands-and-knees crawlers, indicating that the walker group was as likely as the hands-and-knees crawlers to deploy attention differentially to far

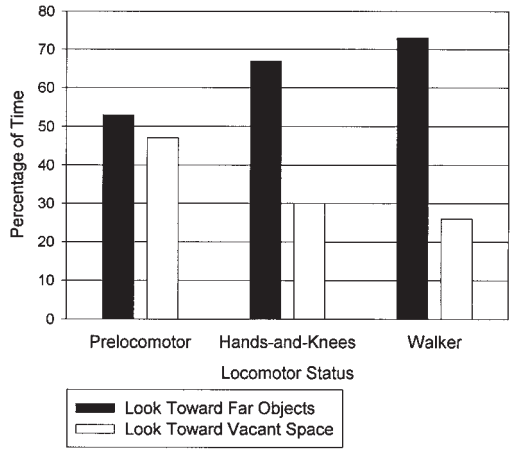

FIGURE 8 Time spent looking at objects in far space versus at vacant areas in far space as a function of locomotor status.

space. Overall, these results indicate that locomotor infants are more discriminating in their attentional deployment than prelocomotor infants.

Further links between development and deployment of attention to distances. Taken in conjunction with the findings by Higgins (1994) and Gustafson (1984), Freedman's (1992) results strongly suggest that infants direct their attention differently to near and far space as a function of locomotor experience. These results are also consistent with some observations of infants' allocation of attention early in life. For example, McKenzie and Day (1972) examined 6- to 20-week-old infants' looking time to objects at 30, 50, 70, and 90 cm. The infants were tested with a series of objects that were either constant in size (and therefore varied in retinal size as a function of distance) or increased in size systematically so that they projected the same retinal size. For both conditions, there was a linear decrease in looking times as a function of distance from the infant. Furthermore, there was no difference in looking time between the younger (6–12 weeks) and older (13–20 weeks) infants. These results have been confirmed with 22-week-old infants by Field (1975) and with 9- and 16-week-old infants by McKenzie and Day (1976). However, the latter authors also showed that as the distance of the object from the infant increased, there were no decrements in looking time to a moving object. The latter finding raises the interesting possibility that motion in general (motion of the environment and motion of the infant) facilitates the deployment of attention to far space.

In fact, Walk et al. (1988) confirmed a relation between environmental motion, attention, and perceptual development. Walk et al. found that the number of days required to show wariness of heights in dark-reared kittens is profoundly affected by the allocation of attention, as well as by locomotor experience. Using a modification of the original Held and Hein (1963) experiment discussed earlier, Walk et al. tested kittens in six different groups, of which only two are critical to our concerns. Both groups of kittens were reared in total darkness, except for 3 hr a day during which they were exposed to the experimental manipulation while restrained in a specially built box. For one group (the go-cart group), the box was placed on a motorized skateboard that moved forward if the kitten raised its head to close a switch. For the other (the car-watching group), the kittens were not given any sort of self-motion, but instead were presented with an interesting display consisting of toy cars moving around a figure-8 track.

There were two critical findings in this study. First, the car-watching and go-cart groups avoided the deep side of the visual cliff with significantly fewer days of testing than kittens that were raised in total darkness or that received no self- or environmental motion. These findings demonstrate that, even in the absence of locomotor experience, attention to the environment can be critical for this developmental transition. Second, Walk et al. (1988) demonstrated that in the absence of either a moving environment that captures attention or locomotor experience avoidance of heights does not develop normally. These results indicate that although locomotor experience might be sufficient for the development of wariness of heights on the visual cliff, it is not necessary. Walk et al.'s data can also document the principle of equipotentiality described in the introduction: It seems that adaptive reactions to heights can result from the mediation of attention, in addition to the locomotion-generated proprioceptive decoupling process described in the previous section.

If, as suggested by these studies, locomotion encourages a reallocation of attention to near and far space, then we would predict three changes in perceptual abilities following the onset of locomotion. First is improved size and shape constancy at relatively large distances from the infant, second is a change in the use of monocular static information specifying depth relations, and third is an increase in veridical distance perception, as consequences of changes in the use of depth information. We now detail our rationale for expecting such changes.

The Redeployment of Attention in the Perception of Size and Shape Constancy

In support of our claim that an ability demonstrated early in infancy will undergo subsequent developmental changes as a function of specific experiences, there is evidence that size constancy improves until 10 or 11 years of age (Beryl, 1926;

Day, 1987; Shallo & Rock, 1988; Wohlwill, 1963). In addition, highlighting the relation between size constancy and distance perception, Wohlwill (1963) noted that distance constancy develops throughout childhood. Other research (Granrud, 1986) showed improvements in an extant perceptual constancy ability even within infancy. Granrud (1986) reported that with the onset of stereoscopic perception at approximately 4 months, there is a step-function increase in infants' size constancy. Specifically, Granrud found that 4-month-olds sensitive to retinal disparity showed better evidence of size constancy than infants of the same age who were not yet sensitive to disparity. Extending the logic of Granrud's study, we maintain that following the onset of locomotion there might well be further calibration of size constancy at greater distances than used by Granrud, especially because Granrud habituated infants over distances of only 30 to 155 cm and tested them at distances of 55 to 105 cm. These distances are still within the range of near space as defined by Johansson (1973). In other words, with the onset of disparity sensitivity, size constancy improves; why, then, should constancies not improve further with the acquisition of locomotor as well as other experiences?

Finally, McKenzie, Tootell, and Day (1980) reported a failure of size constancy in 6- and 8-month-old infants at relatively great distances from the infant (3 m), but not at relatively close ones (1 m). Interestingly, in a second experiment, McKenzie et al. showed that 4-month-old infants, given a dynamic display that is more likely to attract attention, demonstrated constancy at a larger distance. We take this pair of investigations as suggesting the importance of the role of self- or environmental motion in educating or optimizing attention. Specifically, only when the infant's attention is attracted toward the display is information for constancy used veridically.

Taken as a whole, the previously mentioned studies highlight Haith's (1990, 1993) notion of *partial accomplishments.* As Haith (1993) noted,

> The problem is that we find a shred of evidence that a piece of a process is functional and then infer that the whole process is intact, at least implicitly. But, we only have evidence for a partial accomplishment, and we need conceptual schemes that will accommodate such partial accomplishments.… In addition, we often fail to recognize that a baby might "have" a skill at one moment and not the next. (p. 358)

We feel that this reconceptualization of development is critical to understanding the role of locomotor experience in the transitions we are discussing here.

Locomotor Experience and the Development of Sensitivity to Monocular Static Information

On a priori grounds alone, we would not predict that there should be any relation between locomotor experience and the use of monocular static information, because

the normative age for the development of sensitivity to this source of information precedes the normative age for the onset of prone progression. Between the ages of 5 and 7 months, infants begin to reach toward the "apparently nearer" of two objects specified by monocular static information such as linear perspective, texture gradients, and familiar size (Granrud, Haake, & Yonas, 1985; Granrud & Yonas, 1984; Yonas & Granrud, 1985; Yonas, Granrud, Arterberry, & Hanson, 1986). However, with increasing experience, children and adults are acutely aware of the illusion of depth and no longer make this error (Haber, 1980; Koenderink, 1999). Curiously, there is evidence that a reduction in the tendency to reach for the apparently nearer of two objects on the basis of monocular static information is related to locomotor experience. This decline can result from the increasing effectiveness of motion parallax following the onset of SPL.

Using an age-held-constant design, Arterberry, Yonas, and Bensen (1989, Experiment 2) reported that prelocomotor infants, belly crawlers, and hands-and-knees crawlers reached for an object that was apparently nearer on the basis of information contained in linear perspective and texture gradients, on 74.5%, 66.9%, and 63.1% of the trials, respectively. Although suggesting that greater locomotor experience results in less reaching for the apparently nearer of two objects, this trend was not significant. However, a study conducted independently by Thomas and Crow (1988), using similar methodology, did obtain significant results. These authors reported that infants with locomotor experience were significantly less likely to reach toward an apparently nearer object on the basis of the monocular static information associated with familiar size. Taken together, these findings not only implicate locomotor experience in infants' increasing resistance to the illusion of depth but also suggest that such resistance is evident across different sources of monocular static information. It is possible, as Arterberry et al. (1989) noted, that

> With increasing motor experience, infants become more sensitive to the conflicting information for the orientation of the surface. Whereas static-monocular information specifies depth, accommodation and motion parallax provide information that the upper and lower objects are at the same distance. (p. 981)

Explaining the decline in effectiveness of pictorial depth information for reaching. We predict that infants will attend more to motion parallax information following the onset of locomotion and consequently will be fooled less by monocular static information presented in pictorial displays. This argument is premised on the increasing ease with which motion parallax information can disambiguate surface relations following refinements in visual–vestibular coupling (improvement in this coupling following locomotor experience was discussed in the previous section). There is considerable evidence in the adult literature to support the important role of vestibular information in the utilization of motion parallax

(Cornilleau-Pérès & Gielen, 1996; Hayashibe, 1991; Rogers & Graham, 1979; Rogers & Rogers, 1992). Generally, this evidence suggests that surface relations specified by motion parallax alone are ambiguous unless augmented by nonvisual sources of information specifying self-motion.

Therefore, with locomotor experience, information from the vestibular system might be increasingly utilized by the visual system to disambiguate motion parallax information specifying surface layout. Although seated infants might make use of vestibular information stemming from small head motions to disambiguate motion parallax, we believe that the self-motion that takes place over larger distances in locomotion serves as a much better disambiguator of motion parallax. Consequently, locomotor infants can become more aware than prelocomotors of the discrepancy between the depth relations specified by monocular static information and those specified by motion parallax. Growing sensitivity to discrepant depth relations would then lead to a reduction in infants' reaching behavior toward pictorial displays containing illusory depth relations. We feel that this hypothesis should be tested in future research.

Self-Produced Locomotor Experience, Attention, Depth, Distance, and Constancy

Thus, it seems plausible that the role of locomotor experience in the calibration of distance perception is not the ability to detect invariants per se. Rather, it is the ability to integrate the information from those invariants into a coherent perception of space. It must be noted here that our entire discussion is premised on the distinction between depth and distance information.

Traditional accounts of visual development indicate that infants are sensitive to a number of sources of depth information very early in life (e.g., Timney, 1988; Yonas, Arterberry, & Granrud, 1987; Yonas, Granrud, & Pettersen, 1985). However, there is no evidence that infants perceive distance relations in a wholly veridical manner. The problem is that most of the traditional accounts have examined sources of information that specify only relative depth relations. An example of relative depth perception is the perception that a person's hand is farther than a person's outstretched arm, but closer than an object a person is reaching for. Relative depth information, as its name implies, specifies relations between surfaces and objects in ordinal terms. However, to perceive distance veridically, a person also needs to perceive absolute distance information. That is, a person must know exactly how far to stretch an arm to reach an object. For absolute distance perception, the various sources of relative depth information must be calibrated by one or another type of metric information. One type of metric information can be provided by motoric factors, including locomotor experience. We thus expect major changes in absolute distance perception as a function of locomotor experience,

even in infants whose relative depth perception is already quite good. If our reasoning is correct, Berkeley and Piaget might not have been entirely wrong in their suppositions about distance perception—at least not for the perception of relatively large distances.

In summary, we have provided evidence in this section to show that locomotor experience can be responsible for changes in allocation of attention. This change in attention will modify the use of various sources of depth information, which are related to accurate distance perception. Accurate distance perception also leads to marked improvements in size and shape constancy. Our argument implies that distance perception and each of its component factors do not operate effectively over large ranges until the infant has had sufficient locomotor experience to disambiguate those features of the environment that remain invariant following large changes in perspective. Interestingly, our analysis again implicates attention to the environment as a critical mechanism by which developmental changes occur. Some evidence suggests that movement in the environment can elicit precocious perceptual abilities or facilitate their development. Perhaps such a finding should not surprise us. The invariant features of objects, places, and events can be detected both by noticing characteristic patterns of change in global optic flow (i.e., when the observer is moving through the environment) and local optic flow (i.e., when objects and other people are moving through the environment). No doubt, infants' predisposition to attend to movement facilitates the detection of environmental invariants. Finally, we should note the important role of visual–vestibular coupling in the veridical perception of distance. Like attention, such coupling between visual and vestibular information can be a general mechanism underlying the development of a range of perceptual changes.

LOCOMOTOR EXPERIENCE AND SPATIAL SEARCH

Infants between the ages of 8 and 12 months are able to retrieve an object hidden within reach at one location but often have difficulty finding an object when it is hidden under one of two adjacent locations, even when those hiding locations are perceptually distinct (Bremner, 1978; Piaget, 1954). Most curious, however, is that following repeated object retrievals at one location (conventionally denoted as A), infants often make an erroneous reach back to hiding location A when they observe the object moved to a second hiding location (denoted as B). The error, commonly referred to as the A-not-B error, becomes more pronounced as the delay between hiding and search at location B increases. Observed by Piaget (1954) and made an important basis for his stress on the role of action in sensorimotor development, the error was the focus of intense scientific scrutiny during the 1970s and 1980s (Wellman, Cross, & Bartsch, 1987) and has recently received attention anew (Munakata, 1998; Smith, Thelen, Titzer, & McLin, 1999). Piaget (1954) explained

the A-not-B error on the assumption that infants younger than 8 months coded object positions relative to the self (egocentrically) and were unable to relate objects to each other (allocentrically or geocentrically). Contemporary explanations suggest that this notion is too simplistic and implicate a number of other relevant factors (e.g., Munakata, 1998; Smith et al., 1999). It is also important to note that the explanation involving an egocentric to allocentric shift in localization cannot account for an infant's failure on the two-position hiding task described initially, suggesting, perhaps, that different mechanisms underlie performance on this task and the more difficult A-not-B task. Most important for the present purposes, however, is the robust link that has been established between locomotor experience and performance on the A-not-B task (e.g., Smith et al., 1999), as well as variants of the task that tap spatial search skills.

The Initial Evidence for a Link Between Self-Produced Locomotor Experience and Spatial Search

A link between locomotor experience and spatial search was suggested long ago by Piaget (1954), and more recently postulated by Campos et al. (1978), Acredolo (1978, 1985) and Bremner (e.g., Bremner, 1985; Bremner & Bryant, 1977). However, Horobin and Acredolo (1986) were the first to directly test whether locomotor experience had any bearing on the ability to find hidden objects. Horobin and Acredolo tested 34- to 41-week-old infants with varying amounts of locomotor experience, using three variations of the A-not-B task; one in which the two hiding locations were spaced close together, one in which the hiding locations were far apart, and one in which six hiding locations were used. The results showed clearly that infants who had more experience moving independently were more likely to search correctly on the B trials across all three conditions. Furthermore, the most attentive infants in the study were those who had been sitting and moving independently for the longest period. Not surprisingly, the authors speculated that locomotor experience mediated performance on this type of task by facilitating general attentiveness as well as the deployment of attentional strategies such as "keeping an eye" on the correct hiding location.

The findings reported by Horobin and Acredolo (1986) were replicated and extended in a rigorous series of studies by Kermoian and Campos (1988). Experiments 1 and 2 in the Kermoian and Campos series compared the performance of 8.5-month-old prelocomotor infants, prelocomotor infants with walker experience, and locomotor infants with hands-and-knees crawling experience on a series of spatial search tasks designed by Kagan, Kearsley, and Zelazo (1978). The tasks varied in difficulty from retrieving an object partially hidden under one cloth, to the classic A-not-B task with a 7-sec delay between hiding and search, to a variation of the A-not-B task involving the substitution of an object for the one origi-

nally hidden. Infants were given a score based on the number of tasks that were passed. The results indicated that the infants with hands-and-knees and walker-assisted locomotor experience performed significantly better than the prelocomotor infants. Furthermore, when the hands-and-knees and walker-assisted groups were divided further based on the amount of locomotor experience (1–4 weeks, 5–8 weeks, and 9+ weeks), there was clear evidence for improved spatial search scores the longer the infant had been locomoting independently. Again, there were no differences between the hands-and-knees crawling and walker groups.

Analysis of performance on selected individual tasks further highlighted the important role of locomotor experience on spatial search. Forty-two percent of prelocomotor infants failed to find an object slid under a single cloth compared to only 12% of infants who had been hands-and-knees crawling for 9 or more weeks. Eighty-seven percent of the prelocomotor infants failed the A-not-B task with a 3-sec delay compared to only 24% of the infants who had been hands-and-knees crawling for 9 or more weeks. Data from Experiment 3 must be considered to understand completely the implications of the Kermoian and Campos (1988) studies. Thirty 8.5-month-old infants with 1 to 9 weeks of belly-crawling experience (a more effortful, much less efficient form of prone locomotion) performed similarly to the prelocomotor infants from Experiments 1 and 2 on the spatial search tasks. Further, unlike hands-and-knees crawling and walker experience, weeks of belly-crawling experience had no effect on search performance. There is a connection here between Horobin and Acredolo's (1986) suggestion that the deployment of attention mediates spatial search and the data from Experiment 3. The more effortful belly crawling can consume nearly all attentional resources, leaving limited attention to notice features of the environment and their characteristic patterns of change (e.g., occlusion and reappearance) that might facilitate spatial search in other contexts.

Evidence From Delayed Crawlers in China

The previous findings have received additional support from a converging line of research in China that was designed to disentangle the role of the age at which locomotion was acquired from the duration of locomotor experience. This project capitalized on the ecologically and culturally mediated delay described earlier in the acquisition of prone progression in urban Chinese infants.

Two studies were conducted. One was cross-sectional and involved testing 34 infants on only one occasion in a modification of the Kermoian and Campos (1988) procedure (the modification primarily involving the addition of delays of up to 13 sec between hiding and finding the toy in the A-not-B delay test). In this study, the infants' ages ranged from 9 to 12 months, and averaged 10.6 months. All 34 infants were able to crawl on hands and knees for 2.5 m. The infants' data were

expressed as a function of the weeks of locomotor experience the mothers reported when the infants were tested. Age was controlled statistically by an ANCOVA.

The second study, which was cross-sectional, revealed two noteworthy findings. First, age had no significant effect on A-not-B delay performance, whereas locomotor experience did. A follow-up analysis, which partialed out the effects of age on A-not-B delay, revealed a robust effect of the duration of locomotor experience ($p < .008$). Second, when the data were graphed and analyzed in terms of the duration of locomotor experience reported by the mothers, there was a clear monotonic trend between infants' performance and the duration of locomotor experience (see Figure 9). This study thus suggested that the trend reported by Kermoian and Campos (1988) for infants at 8.5 months of age is evident even when infants begin to crawl at somewhat later ages. Indeed, within the limits of age tested (which in China extended to ages when some Western infants have begun to walk, not just crawl), age had no evident influence on the obtained results.

This cross-sectional work was followed up in China with a longitudinal study. Infants were recruited for the study when they were 7 months of age, and followed up by home visits until the investigators determined that the infant had begun to crawl on hands and knees for 2.5 m without stopping, slipping, or untangling the legs. This locomotor milestone was achieved at different ages, allowing the Chinese investigators to perform a lag-sequential analysis of their data. That is, regardless of the age when the infants began to crawl, they were tested on the A-not-B delay test used in the cross-sectional study after they had approximately 4 weeks, 7 weeks, and 10 or more weeks of locomotor experience. The results of the

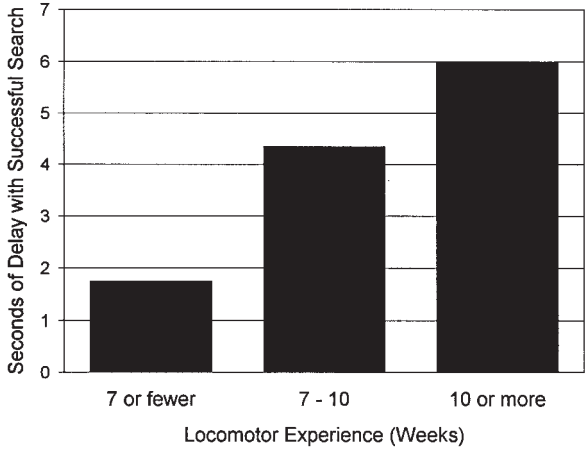

FIGURE 9 Performance of Chinese infants tested once cross-sectionally on the A-not-B delay task as a function of locomotor experience (data from Tao & Dong, 1997).

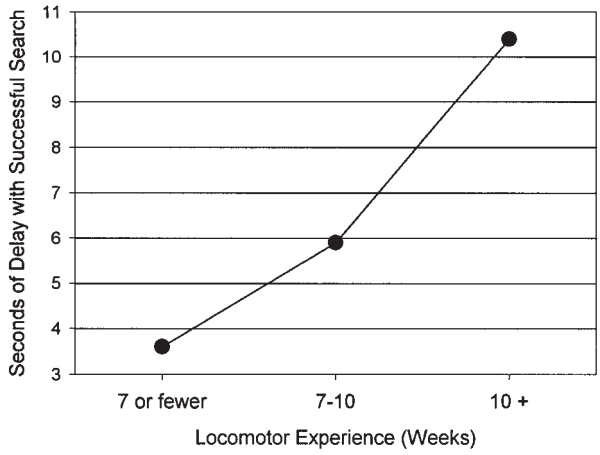

FIGURE 10 Performance of Chinese infants tested longitudinally on the A-not-B delay task as a function of locomotor experience (data from Tao & Dong, 1997).

longitudinal study, averaged across all participants, are presented in Figure 10. As can be seen, there is again a clear monotonic trend indicating improvement in A-not-B delay performance as a function of locomotor experience.

The lag-sequential analysis of this longitudinal study allowed a test of the effects of age of crawling onset separately from the duration of locomotor experience. This dissociation was accomplished by dividing the infants into those who began to crawl at an age that is normatively early for China (approximately 8.5 months), normatively late for China (approximately 11 months), and an in-between age. These data are presented in Figure 11. As can be seen, each of the early, normative, and late-crawling-onset groups shows the same monotonic increase in performance as a function of locomotor experience. The only suggestion of an age effect is the steeper gradient in improvement in performance for the normatively late-crawling-onset group. Although the sample size in the lag-sequential analysis is small ($n = 3$ per group), these data suggest that the duration of locomotor experience facilitates tolerance of increasing durations of delay between hiding and finding an object on an A-not-B task. Furthermore, a potential criticism of the longitudinal data (viz., that the improvement with locomotor experience involves the effects of repeated testing) cannot apply to the highly similar findings from the cross-sectional study, in which infants were tested only once, and in which the sample size was much larger.

Evidence from infants with motor disabilities. The study of motoric delays in China resulting from ecological and cultural factors raises important ques-

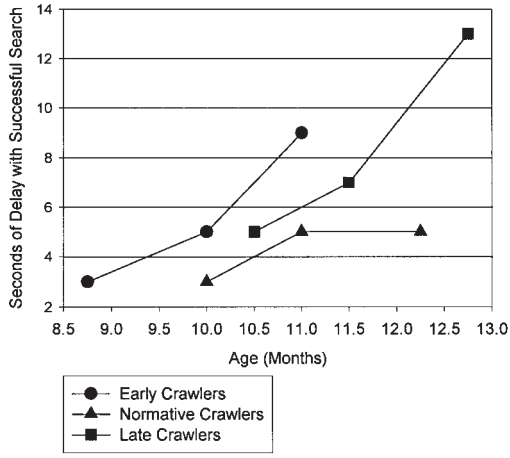

FIGURE 11 Performance of Chinese infants tested longitudinally on the A-not-B task as a function of both age of onset of crawling, and locomotor experience. Each curve represents data from three infants (data from Tao & Dong, 1997).

tions about the consequences of locomotor delays in children with neurological, orthopedic, or other medical conditions that delay the onset of locomotion. For many years, researchers have questioned whether locomotor experience is necessary for the development of aspects of sensorimotor intelligence. As mentioned in the introduction, the work of Decarie (1969) and Kopp and Shaperman (1973) suggested that locomotor experience is not necessary for the development of sensorimotor skills. However, our research, taken as a whole, suggests strongly that crawling experience can be an important organizer of psychological development, especially in the realm of manual search for hidden objects. We confirmed that implication in the aforementioned study of 7 infants with spina bifida by Telzrow (Telzrow, 1990; Telzrow et al., 1987; Telzrow et al., 1999).

In addition to studying referential gestural communication, Telzrow's study examined spatial search on a two-position hiding task (patterned after a study by Bremner & Bryant, 1977), in which an object was hidden under one of two perceptually distinct covers (Telzrow et al., 1987; Telzrow et al., 1999). In this paradigm, infants saw the object hidden only in one location; the second location served only as a distractor. As mentioned earlier, infants were tested once a month, at the same session as the one assessing referential gestural communication. Testing began at the age of entry into the study until 2 months after the onset of SPL.

The results showed unequivocally a dramatic improvement in spatial search performance following the onset of locomotion. Prior to locomotion, infants passed only 14.3% of the trials; following locomotion, infants passed 64.3% of the trials.

This trend was evident in 6 of the 7 infants tested. As in the work of Horobin and Acredolo (1986), Telzrow et al. (1999) noted that after the onset of locomotion, the infants with spina bifida tended to be much less distractible, more task oriented, and more likely to align their heads, eyes, and bodies toward the hiding location during the delay between hiding and search than before the onset of locomotion.

The study by Telzrow et al. (1999) was conducted simultaneously in Denver, using an age-held-constant study of 8-month-olds, with the same two-position hiding procedure. Infants were divided equally into three groups: crawling (n = 16), prelocomotor with walker experience (n = 12), and prelocomotor (n = 24; Campos, Benson, & Rudy, 1986). The two groups with locomotor experience performed almost identically (around 72% correct search on the hiding trials), and very differently from the prelocomotor infants without locomotor experience (who successfully retrieved the object hidden under one of the two cloths only 17% of the time).

In sum, regardless of whether infants are tested with a two-position hiding task or an A-not-B task with a few seconds of delay, crawling infants and prelocomotor infants with walker experience far outperform infants with no locomotor experience. Furthermore, these findings are obtained cross-sectionally, longitudinally, across at least two cultures, and appear to be independent of the age of onset of crawling, within the age limits investigated to date.

By What Processes Are Spatial Search and Locomotor Experience Linked?

Despite the intense scrutiny given to the A-not-B error, and to a lesser extent, performance on two-position hiding tasks, the processes by which spatial search ability improves are still poorly understood. Without doubt the phenomenon is extremely complicated, especially when a person considers that it is necessary to explain the spatial component of spatial search (i.e., how is the correct location selected?) in addition to the temporal component (i.e., why do increasing delays between hiding and search degrade performance?). Nevertheless, several processes have been proposed to account for the development of spatial search performance and here we outline our view of how locomotor experience mobilizes these processes. The processes underlying improvements in spatial search include: (a) shifts from egocentric to allocentric coding, (b) learning of new attentional strategies, including improved discrimination of task-relevant features, (c) refinements in means–ends behavior and an associated tolerance of longer delays in goal attainment, and (d) improved understanding of others' intentions. We discuss the relation between each of these processes and locomotor experience.

Shift from egocentric to allocentric coding. Piaget (1954) was one of the first to suggest that improvements in spatial search represent the infant's emerging

ability to shift from egocentric to allocentric coding strategies. The idea stems from an observation of the prelocomotor infant's world, a world that is very proximal and generally acted on from a stationary position. Under such conditions, an egocentric reference system is sufficient to learn how to move body parts relative to one another and to reach for objects. However, remaining oriented once mobile is a different problem, because an egocentric reference system, unless updated, will not be as useful as an allocentric reference system in which the positions of environmental features are coded relative to each other. Although a simple shift from egocentric to allocentric referencing can partly explain improvements in spatial search, it should be kept in mind that it cannot explain the improvements in search performance on two-position hiding tasks following locomotor experience (e.g., Campos et al., 1986; Telzrow, 1990). The two-position hiding task involves no trials in which a toy first hidden at A is subsequently hidden at B; as said before, the second position is a mere distractor. Our findings with the two-position task suggest that the transition engendered by locomotion is likely to result from multiple processes.

The role of attention. Acredolo and colleagues (e.g., Acredolo, 1985; Acredolo, Adams, & Goodwyn, 1984; Horobin & Acredolo, 1986) were the first to note a relation between locomotor experience and visual attention during "hide-and-seek" tasks like those used in the A-not-B paradigm. Quite simply, infants who kept an eye on the correct hiding location tended to search correctly for the hidden object. For a mobile infant, keeping an eye on objects and the places where they have disappeared is an effective way to find them again. However, there is more to attention than simply keeping an eye on certain targets. As Acredolo (1985) suggested, visual tracking of spatial locations can simply be a transitional strategy as infants learn what information from the self and the environment must be attended to in order to refine egocentric and allocentric coding strategies.

Earlier, it was noted that through a process akin to the education of attention, infants learn to use spatially delimited portions of the optic array for controlling the important subtasks involved in locomoting to a destination. The same type of selective attention is likely involved in the spatial discriminations necessary to localize distal targets and successfully steer a course to a target and return. Not surprisingly, the increasing ability to make fine-grained spatial discriminations has been suggested as one means by which locomotor experience might contribute to improved performance on the A-not-B task (Smith et al., 1999). The premise here is that the classic A-not-B task presents a perceptually confusing context in which reaching and search errors are very likely to occur. This argument is bolstered by the observation that search on B trials improves when the A and B hiding locations are perceptually distinct and easily discriminated (Wellman et al., 1987).

Related to this idea is the notion that better discrimination might also facilitate performance on the two-position hiding task, even when the hiding locations in these tasks are perceptually distinct. This argument is tenable if a person assumes

that the learning of new motor skills initially directs an infant's attention to the features of the environment that specify the affordances for the new skill (e.g., Gibson & Schmuckler, 1989; Schmuckler, 1993). These features include the physical properties of the environment to which movements must conform, what Gentile (1987) referred to as the regulatory features of the environment. In a spatial search task, the position of the target relative to the infant, and the size, shape, weight, and texture of the hiding cover would be regulatory features. Once infants have become attuned to the important regulatory features of the environment, they might begin to notice the background or nonregulatory (Gentile, 1987) features of the environment, such as the color of an object. In other words, the infant would show a progression in the detection of information as skill proficiency improves from those features directly related to the control of action to those that are indirectly related but can nevertheless facilitate performance on tasks like spatial search.

With reference then to spatial search performance, locomotor experience likely has a broad impact on the development of attentional skills that generalizes to contexts other than those involving locomotion. Locomotor experience facilitates the development of new attentional strategies and leads to the detection and extraction (discrimination) of information most relevant to the task at hand. This argument is supported further by the common observation that locomotor infants are generally more attentive and less distractible during hide-and-seek tasks than prelocomotor infants. The argument also explains why belly crawling (which is an inefficient means of prone locomotion that consumes considerable energetic and attentional resources) should facilitate neither the development of attentional skills nor the subsequent development of spatial search skills.

Refinements in means–ends behavior and tolerance of delays in goal attainment. Although the previous explanations can adequately explain the spatial component of the A-not-B error, they do not account for the observation that the likelihood of the error increases as the delay between hiding and search lengthens and that older infants and those with more locomotor experience are capable of tolerating longer delays. What role does locomotor experience play here? Quite possibly, locomotor experience demands and sets up the contingencies associated with the development of more sophisticated means–ends behavior and the ability to tolerate delays in goal attainment.

When an infant locomotes toward an environmental goal, the goal must be kept in mind over the period of time necessary to reach the objective, particularly if the target is somehow occluded during any portion of the movement toward it. Furthermore, the act of locomotion requires sophisticated means–ends behavior. Contrary to a discrete behavior such as reaching for a single object, locomotion demands a concatenation of movements over time—specific movements are nested within higher order movement sequences in the service of goal attainment. That deficits in means–ends behaviors have been implicated in the A-not-B error

(e.g., Diamond, 1991; although see Munakata, McClelland, Johnson, & Siegler, 1997) is of special interest in the proposal here. However, the primary suggestion we make is that the establishment of action intermediaries in means–ends behavior has a counterpart in the time domain that is then associated with the ability to tolerate longer delays in goal attainment. In other words, locomoting to achieve a goal takes time. The infant must keep the goal in mind and must sequence (concatenate) a number of movements over time if the goal is to be achieved. It may be in this sense that locomotor experience leads to improvements in means–ends behaviors and to the ability to tolerate longer delays in goal attainment.

The development of interintentionality. The final process linked to locomotion and underlying improvements in spatial search performance is the development of interintentionality. The phenomenon of interintentionality is similar to the social referencing phenomenon and the understanding of referential gestural communication in that it involves the processing of communicative signals from others. However, interintentionality refers specifically to an understanding that others have intentions and the nature of such intentions. Based on observations of infants performing the A-not-B task in our lab, locomotor infants appear not only more attentive and less distractible than prelocomotor infants but they appear also to actively search for communicative signals from the experimenter. It is as if they work harder to understand the "game," as it were, and try to glean such an understanding from the experimenter. Perhaps this observation should not be surprising given the evidence provided previously for increased checking back and increased understanding of referential gestural communication following locomotor experience. Although based only on serendipitous observation, we feel strongly that the role of interintentionality in spatial search performance should be examined further, especially in two-position hiding tasks, where our serendipitous observations have been made.

To recapitulate, a number of converging research operations have shown a robust link between experience with self-produced locomotion and performance on spatial search tasks. The onset of locomotion leads to a number of new encounters with the environment and an accompanying need to extract new information and solve new problems. We have argued that the experiences associated with these encounters lead to general changes in attentiveness, to the specific deployment of attentional strategies as well as the education of attention to important features in the environment, to refinement of means–ends behaviors, and to the development of interintentionality. Consequently, these processes are implicated in the development of more sophisticated spatial search strategies and the appropriate deployment of such strategies across changing tasks and contexts. The specific role of these processes in the development of spatial search skills, as well as the interactions among them, awaits further research.

EXPERIENCE WITH SELF-PRODUCED LOCOMOTION, SPATIAL CODING STRATEGIES, AND THE DEVELOPMENT OF POSITION CONSTANCY

In this section, we discuss spatial coding strategies and position constancy. The former refers to the means by which infants search for objects in space following self-movement, and the latter refers to the accurate outcome of a search strategy after self-movement. Here, we explain why there should be a robust link between SPL and spatial coding strategies. We also place the data on the use of such strategies in early infancy into a developmental context. Finally, we highlight a number of variables that might mediate the effects of locomotor experience on the development of spatial coding strategies and position constancy.

Self-Referent and Environmental Referent Coding Strategies

In the previous section, we discussed Piaget's (1954, 1970) ideas about how the infant in early life undergoes a developmental sequence in which objects are first localized through the use of egocentric or self-referent (SR) spatial search strategies. An SR strategy involves the infant locating objects either by determining where it is in relation to the infant's body, or by repeating the actions that were previously successful. For example, an infant who finds an object on the right will continue to look to the right in subsequent attempts, even if the infant moves so that a rightward search is no longer appropriate. During the second step of Piaget's developmental sequence, which is thought to occur during the third quarter of the first year of life, the infant begins to replace SR strategies and use evironmental referent (ER) strategies to locate objects. Unlike SR strategies, search based on ER involves relating at least two environmental events or objects to each other, independent of the position of the self. ER strategies are much more likely to result in position constancy, because an object's position in space relative to other objects is generally invariant despite shifts in body movement. However, it was also noted previously that an egocentric strategy is not always inaccurate, provided the egocentric reference system is updated following self-movement. In other words, spatial orientation can be maintained if (a) the position of the self relative to the target location is noted prior to displacement, and (b) the direction and extent of movement of the self is continuously monitored. With such monitoring of self-movement, the new position of the target location relative to the self can be computed. Note, however, that in this section we do not discuss the role of locomotor experience on updating SR strategies, because evidence has yet to be provided for a link between these two variables, at least not at the ages we are concerned with here.

Piaget (1954) implied, and Acredolo (1985) and Bertenthal et al. (1984) explicitly proposed, that motoric activity, especially locomotion in space, facilitates the construction of ER strategies. In this section, we review some hitherto-undiscussed research on the role of locomotor experience on SR and ER use and draw two conclusions. One is that there is a developmental shift toward increasing probability of ER strategy use, and the second is that locomotor experience, contrary to some reviews (McKenzie, 1987), does play a role in that shift.

Several researchers have studied infants' use of these different strategies using two different types of displacements: rotations up to 180° and rotations up to 180° combined with translation (see Figure 12 for clarification of these two different kinds of displacements). Typically, the infant is taught to localize a target object from an initial vantage point, then displaced and tested to determine whether that infant can relocalize the target from the new vantage point. The task can be accomplished using a looking or a reaching movement with or without the aid of specific landmarks. The general consensus is that before 6 months of age, infants are unable to show position constancy after any of the types of displacement shown in Figure 12 (for reviews, see Acredolo, 1985; Bremner, 1993b). Between 6 and 8

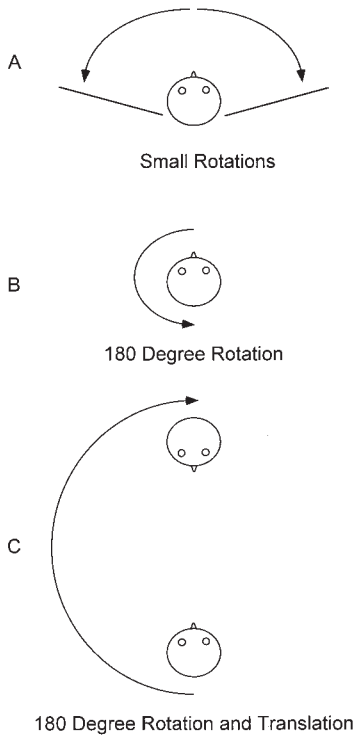

FIGURE 12 Illustrations of rotation (defined as the infant pivoting left or right, but staying in the same place) versus rotation and translation (defined as the infant pivoting left or right and also moving from one place to another). A small rotation is one that is less than 180°.

months, infants are more successful at such constancy, but only if they are minimally rotated—no more than 90° (J. G. Bremner, personal communication, March 18, 1999; McKenzie, 1987; Rieser, 1979). After 8 months, infants are shown to be progressively more capable of relocalizing a target after larger rotations, with or without translation, as long as the landmark is available to the infant (Acredolo, 1985; Acredolo & Evans, 1980; Cornell & Heth, 1979; Lepecq & Lafaite, 1989).

Given the prior findings, locomotor experience does not seem necessary for the development of some degree of ER use and hence position constancy. Rather, this early use of ER search can be linked to the development of sitting and reaching (Bremner, 1993a). Our reading of the literature suggests that position constancy and ER use is likely to be evident precociously (relative to Piaget's expectations) under the following four circumstances:

1. The environmental referent is close to, or even adjacent to, the searched-for object, rather than at some distance from it (Acredolo & Evans, 1980; Bremner, 1978).
2. The landmarks are salient (Acredolo & Evans, 1980).
3. Infants are tested in familiar environments, such as the home (Acredolo, 1979, 1982).
4. No training trials are presented during initial localization of the target (Bremner, 1978).

Limitations in Prelocomotor Use of ER Strategies

Given that several studies have shown the ability to use ER strategies quite early in life, why have several authors hypothesized a strong link between locomotor experience and the development of spatial skills? (For reviews, see Acredolo, 1978, 1985; Bremner, 1993a; Bremner & Bryant, 1977; Lepecq, 1990, but for a sharp objection, see McKenzie, 1987). One reason is that the extent of ER use by infants who can sit and turn their heads and torsos will be constrained because of the limited nature of the experiences made possible by sitting, turning, and reaching. A second reason is that SPL contributes to ER use in situations where the landmarks are well beyond reach or in the extreme periphery of the infant's vision. (We have already seen the possible importance of growth of the infant's peripheral visual field in the research described previously on referential gestural communication. In that work, an infant capable of success when signaler and target are in the same visual field cannot succeed when signaler and target are in different visual fields.) Demands on the locomotor infant are very different from demands on the prelocomotor, seated infant. In addition, the deployment of ER strategies is especially likely when the infant is displaced in a forward direction by some minimal distance. Such forward displacements are common after prone progression, and rare prior to it.

There can be yet another reason for expecting a link between locomotor experience and spatial coding strategy use. To relocalize targets, and hence show position constancy, mobile infants must pay close attention not only to the environmental layout but also to their own movement with respect to the environmental layout. We discussed already the refined coupling between various sources of perceptual information following locomotor experience. Such coupling should facilitate the ability to track a person's own movement, and therefore, contribute to the ability to update egocentric responding after larger and larger displacements. Furthermore, attention will be directed increasingly toward far space as the infants' targets of locomotion become more distal. Hence, we predict that the ability to use distal landmarks to relocalize target positions should improve markedly following locomotor experience.

Spatial coding strategies provide thus another example of a skill (in this case ER or landmark search strategies) present early in life but not yet fully developed. As a function of specific experiences and adaptation to new contexts, the skill undergoes further development and is deployed in settings where it was not previously evident. We believe that locomotor experience creates new contexts that call for deployment of an existing skill in a more complex way. What empirical evidence, then, supports the role of self-produced locomotor experience in the development of spatial coding strategies?

A Study of Locomotor Experience and Position Constancy

One of the first studies to examine the link between locomotor experience and the use of external referent strategies was carried out in our laboratory by Enderby (1984). Using a paradigm developed by Acredolo (1978; Acredolo & Evans, 1980), Enderby tested, in an age-held-constant design, three groups of 36-week-old infants. One group had no locomotor experience, one had at least 3 weeks of crawling experience, and one had no crawling experience but at least 40 hr of walker use. There were 20 infants per group. Each infant was trained to anticipate the appearance of a person at one of two windows (about 75° to the left or right) within a curtained enclosure. Salient landmarks, including flashing lights around the window, brightly colored stripes, and a blue star on the wall, were used to highlight the target window in an otherwise homogenous 2.7-m × 2.7-m enclosure. Note that in this study, the landmark was distal from the infant, which met one criterion for the type of testing context that would require locomotor experience for successful ER use. A cartoon of the paradigm is presented in Figure 13.

There were two parts to the study by Enderby (1984)—training trials and test trials. On training trials, a buzzer sounded, followed 5 sec later by the appearance of an experimenter at the target window. Training was repeated until the infant

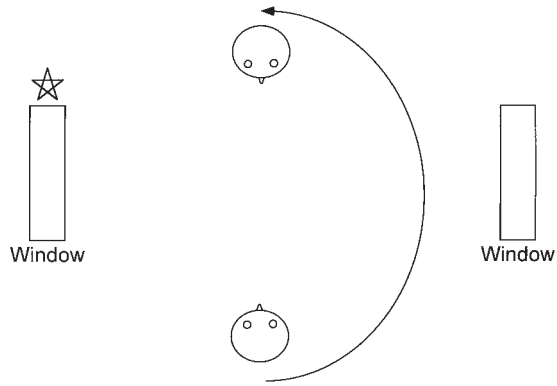

FIGURE 13 Visual depiction of the Acredolo paradigm, in which the infant is rotated 180° and translated by 1.3 m. The starred window represents the landmarked location where the infant initially learned on training trials to expect the emergence of an experimenter.

correctly anticipated the appearance of the experimenter on four out of five trials. Immediately after the training criterion was met, infants were both translated by about 1.3 m and rotated 180° to face the other side of the enclosure, and test trials began. When the buzzer sounded on each of the five test trials, the experimenter no longer appeared at the window. The direction of the infant's looking was examined as the dependent variable.

Results from this experiment revealed that, over all five test trials, 40% of infants with crawling experience correctly anticipated the appearance of the experimenter at the labeled window compared to only 15% of the same-aged prelocomotor infants. Infants with walker experience fell in between (35%). These results, presented in Figure 14, showed that locomotor infants had significantly better position constancy than prelocomotors. A similar pattern of findings was obtained for the first test trial data (Enderby, 1984).

Subsequent Research on Locomotor Experience and Spatial Coding

The results of Enderby's (1984) study were replicated in a study conducted at the University of Virginia by Bertenthal et al. (1984). Using very similar procedures to those of Enderby, the authors reported results for locomotor and prelocomotor infants that showed a trend similar to Enderby's. However, there were two noteworthy differences between the studies. First, Bertenthal et al. reported that walker experience resulted in looking at the correct window on the

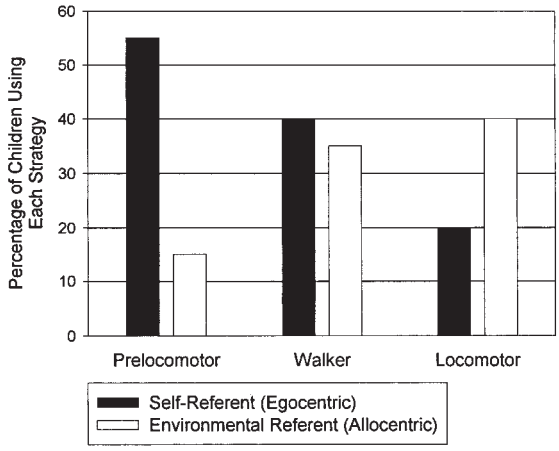

FIGURE 14 Egocentric and allocentric responses of 8.5-month-old infants as a function of locomotor status (data from Enderby, 1984).

test trials a greater percentage of time than crawling experience. In that sense, the Bertenthal et al. study obtained stronger findings than did Enderby's. Second, Bertenthal et al. reported that locomotor infants used an allocentric (ER) strategy on many more trials than did Enderby (74% of trials compared to 40%); on the other hand, the prelocomotor infants used an allocentric code on 56% of trials, compared to 15% for Enderby. Despite these differences, the two studies converge in linking locomotor experience to position constancy on a displacement-plus-rotation task. Adding further strength to the link between locomotor experience and position constancy, Bertenthal et al. described a longitudinal study of an infant with an orthopedic handicap. That infant performed poorly on the Acredolo paradigm until a heavy cast impeding locomotion was removed and the infant became capable of locomotion at a somewhat later than average age.

The results of a study by McComas and Field (1984), also using a paradigm based on Acredolo's (1978) study, are often cited as evidence against the role of locomotor experience in the development of spatial referencing strategies. Their findings superficially appear to fail to replicate the studies by Enderby (1984) and Bertenthal et al. (1984). However, there are several reasons to be cautious about the findings of the McComas and Field study. First, the study seriously confounded locomotor experience and age, in that the older group had more locomotor experience. Second, all infants in that study had some locomotor experience (either 2 or 8 weeks); no prelocomotor group was included to provide a benchmark for comparison with the work of Enderby and Bertenthal et al. Third, the landmark

used to specify the target window (a star around the window) was much less salient than the landmarks used in the Enderby and Bertenthal et al. studies. The relevance of the McComas and Field study to the evaluation of the role of locomotor experience on deployment of ER strategies is thus uncertain.

Also uncertain is the relevance of a study by Glicksman (1987) on the ability of 35-week-old locomotor and prelocomotor infants to relocalize a target object in a spatial rotation task that involved no landmarks. Glicksman's groups included prelocomotor infants, prelocomotors with walker experience, crawlers, and crawlers with additional walker experience. Infants were seated in the middle of a homogenous 2-m × 2-m square enclosure, centered between two identical brass bells, one on the left and the other on the right. One of the bells was movable, and thus, could be manipulated freely by the infant, whereas the other bell was invisibly secured to the floor. First, infants were required to retrieve the movable bell two times in succession during a training period. Then, after watching the bell being replaced in its original position, the infants were rotated 180°. Results from three consecutive training and test trial sequences revealed no differences between the groups in terms of the proportion of infants in each group who reached for the movable bell following rotation. Half of the infants in each group reached for the movable bell, and half reached for the stationary bell.

Given the demanding nature of Glicksman's (1987) task, we are not surprised by her results. Because there are no landmarks, success on this task requires that infants use a sophisticated SR strategy involving the updating of body position—a strategy beyond the capability of infants with limited locomotor ability. Furthermore, body position must be updated following a large rotation, that is, 180°. With a rotation of this magnitude, coupled with the absence of landmarks, it is unlikely that infants would succeed on this task prior to 12 months of age (Acredolo, 1978; Lepecq & Lafaite, 1989).

We thus conclude that the weight of the evidence favors a role for locomotor experience in facilitating correct performance in tasks such as the Acredolo rotation plus displacement task. But do these findings imply that locomotor experience is effecting a developmental shift in spatial coding strategies? Or is there another explanation possible for the findings using the Acredolo paradigm?

The most crucial concern raised about the research on the effects of locomotor experience on spatial coding is the possibility that the Acredolo paradigm involves infants learning a motor habit. As several investigators note (e.g., Bai & Bertenthal, 1992; Bremner & Bryant, 1985; McKenzie, Day, & Ibsen, 1984), a motor habit or response set can conceivably mask an ER or landmark-based coding strategy that the infant in fact possesses. If so, locomotor experience can have more to do with overcoming motor habits than facilitating the deployment of more complex spatial cognitive skills. To overcome this problem, a paradigm should be used that assesses position constancy without using training trials or generating motor habits.

Overcoming the Motor Habit Confound in Spatial Coding Studies

Bai and Bertenthal (1992) conducted precisely such a study and found an effect for locomotor experience on the type of spatial coding strategies used by their infants. Their study adapted a paradigm from Bremner (1978) that minimizes the likelihood of teaching infants an incorrect egocentric response. Infants were tested in a square homogeneous room (2.5-m × 2.5-m) that was free of landmarks. Each infant was seated in the center of the room in a chair attached to a table. The chair allowed the infant to be rotated and locked in two positions 180° apart. Although the paradigm used a set of warm-up trials, in which infants were trained to search for a toy hidden in a single cup, there was no training in the part of the study that assessed position constancy.

In the position constancy test, two different colored cups (different also from those used in training trials) were placed side by side on the table in front of the baby. The infant watched the toy being hidden in one of the two cups and was immediately rotated 180° around the table (corresponding to a translation of approximately 1 m) before being allowed to search (see Figure 15 for a cartoon of the task). Three groups of 33-week-old infants were tested. One group of 20 infants was prelocomotor, a second group of 10 infants had 2.7 weeks of belly-crawling experience, and the third group of 18 infants had 7.2 weeks of creeping experience.

Results revealed that search performance varied as a function of locomotor status, especially on the first trial, with 72% of the creeping infants, compared to 25% of prelocomotors and 30% of belly crawlers showing position constancy (see Figure 16). These findings provide evidence that locomotor experience affects the deployment of spatial coding strategies, even when motor habits play no confounding role. Taken in conjunction with the work of Enderby (1984) and Bertenthal et al. (1984), the role of hands-and-knees locomotor experience is evident in spatial displacement tasks that also involve a rotation.

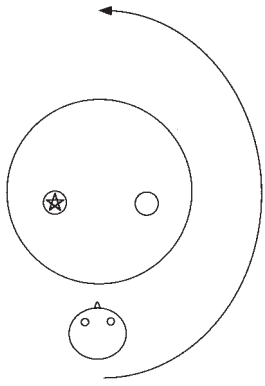

FIGURE 15 Cartoon of the testing apparatus used in the Bai and Bertenthal (1992) study.

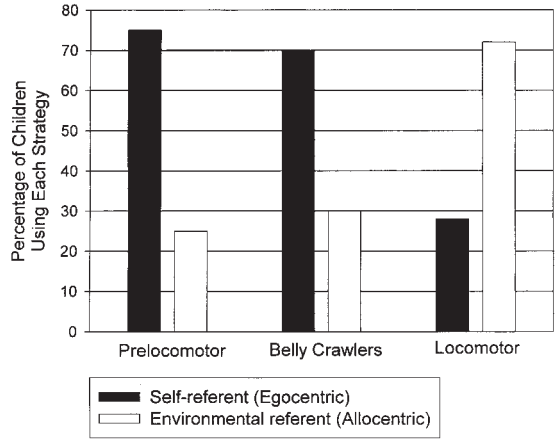

FIGURE 16 Performance of infants differing in locomotor status on a rotation translation task that involved no training trials. Adapted from "Locomotor status and the development of spatial-search skills" by Bai, D. L., & Bertenthal, B. I., 1992, *Child Development, 63*, 215–226. Copyright 1992 by the Society for Research in Child Development. Adapted with permission.

As in the Kermoian and Campos (1988) study, belly crawling did not seem to affect performance in this study. However, the confound in the belly-crawling group between duration of locomotor experience and quality of locomotion precludes any strong inferences about the role of belly crawling on position constancy.

There was another aspect to the Bai and Bertenthal (1992) study that deserves brief mention. They reported no differences between the locomotor and prelocomotor infants when the table, rather than the infant, was rotated. We are not surprised by this result: Rarely would prelocomotor or locomotor infants of this age experience environmental movements involving a static observer and a rotating hiding surface. At some point in development, correct search following table rotation should be evident; however, locomotor experience should not be linked to table rotations in front of a static observer. The effects of locomotor experience should be much more strongly related to position constancy following subject movement.

Making More Robust the Link Between Locomotor Experience and ER Deployment

In sum, the results of the studies cited in this section suggest a positive link between locomotor experience and the use of external landmarks that underlie the development of allocentric or ER spatial coding strategies. However, we believe that the link

between locomotor experience and spatial referent strategies following displacements should be even more robust than has been the case in studies conducted to date.

Why is the link not as robust as we might expect? There are at least three factors that can mediate the effects of SPL on the development of new spatial referent strategies. First, it is likely that the amount of experience needed to bring about a shift in spatial coding strategies has been underestimated. Infants should not be expected to effectively switch from 0% to 100% position constancy. After locomotion emerges, the infant learns through experience that referencing objects and people to themselves as static observers will reliably work under some conditions, but not others (e.g., when moving from place to place). A transitory period is likely to follow, during which infants learn to differentiate those situations that can successfully employ a static self-referent system from those requiring the use of external landmarks to update orientation within the environment. It should not be surprising if, during this period, infants switch back and forth between the two strategies of SR and ER before they begin to consistently show position constancy. Only a longitudinal study will definitively show whether the predominant use of one spatial reference strategy is followed by a period of use of a more complex strategy, with a period of extensive instability in coding strategy use in between. In the meantime, cross-sectional studies should ensure that comparisons are made between infants who are clearly prelocomotor versus those who have considerable locomotor experience.

The second factor that might mediate the effects of locomotor experience on emergence of different spatial referent systems is the type of displacements used by researchers versus the displacements that are typically encountered by actively locomoting infants. The specificity of displacements experienced in locomotion is critical to understanding the limitations of previous studies. Displacements generated by a creeping infant are predominantly linear in nature (involving forward translation). However, the testing situations used in studies of position constancy and locomotion have used large *rotations* (of 180°) accompanied by translations. Translations with rotations are not likely to be experienced very often by creeping infants, although walking infants doubtless often experience them. Consequently, we believe that a more robust link between locomotor experience and spatial reference strategies following displacement can be established if infants are tested in tasks that involve linear displacements, as opposed to rotations or combinations of rotation and translation.

This is not to suggest that rotations are never experienced prior to upright locomotion; certainly, sitting infants regularly experience rotations when they pivot the trunk relative to the base of support and the head relative to the trunk. However, these are small rotations, not on the order of 180°, as used in studies cited previously; nor is translation involved, again as in the studies cited earlier. In fact, some evidence shows clearly that prelocomotor infants are capable of relocalizing targets after only partial rotations.

The third factor relevant to this discussion is the type of landmarks that can be used to maintain spatial orientation. It is important to note the success in relocalizing a target has been most reliably linked to locomotor experience in experiments where landmarks were very salient. Furthermore, it must be noted that in all experiments in which prelocomotors were found to use ER strategies, the landmarks used were spatially coincident with the target and relatively close to the infant. The landmark surrounded the target, and could not be visually separated from it. It is more likely that, relative to prelocomotors, locomotor infants will notice and be more able to use landmarks separated from targets and distal from the infant. The latter part of this hypothesis is based on Freedman's (1992) study, showing that locomotor infants directed more attention to far space than prelocomotor infants. Hence, differences between locomotor and prelocomotor infants' use of ER strategies can be much more apparent in paradigms that make use of distal landmarks, particularly those placed outside of the reaching envelope that typically constrains the perceptual-motor workspace of prelocomotor infants. Another possibility is that locomotor experience will lead to greater sensitivity to landmarks in the peripheral visual field than those in the central visual field.

In summary, we believe that the capacity to show position constancy and landmark- or environmentally based referencing following a displacement is present in narrowly specified contexts quite early in life. As suggested by others (e.g., Bremner, 1993a), the development of motor abilities such as sitting can facilitate the development of spatial coding strategies to some degree. However, we expect that the onset of self-produced locomotion will markedly influence the subsequent development of spatial coding. Specifically, locomotor experience leads to the refinement of strategies and to the development of knowledge about the appropriateness of a given strategy for a specific task and situation.

CAN LOCOMOTOR EXPERIENCE BE MANIPULATED IN A TRUE EXPERIMENT?

Despite the extraordinary number of converging research operations we used in this research project, all of the studies linking locomotor experience and psychological development are quasi-experimental. In no study was random assignment of participants to conditions used (not even in the walker groups, which tested infants whose mothers had decided to provide such devices to their infants). Given the limitations of quasi-experimental research designs for making any strong inferences about causality, we are currently investigating whether locomotor experience can be manipulated in a true experiment to assess the effects of such experience on responsiveness to peripheral optic flow, wariness of heights, and spatial search strategies. Evidence has been provided already that training can accelerate the development of creeping and that such training has an impact on intellectual de-

velopment (Lagerspetz, Nygård, & Strandvik, 1971). However, rather than manipulate the onset of crawling, we have taken our lead from an ingenious experiment by Woods (1975) that tested whether self-produced locomotion had reinforcing properties for prelocomotor infants between the ages of 88 and 109 days. Using a motorized infant carriage, controllable by sucking on the nipple of a bottle that housed a pressure transducer, Woods clearly showed that infants produced higher rates of sucking and longer burst lengths when motion of the carriage was contingent on sucking than when it was not. These findings suggest strongly that prelocomotor infants can learn to control their motion in a powered mobility device (PMD), a notion at the heart of our current endeavors to manipulate locomotor experience in a true experiment.

Some of our preliminary results (Anderson, Campos, Barbu-Roth, & Uchiyama, 1999) showed that prelocomotor infants are quite adept at controlling their forward motion by pulling on a brightly colored joystick mounted at the front of a PMD (refer to Figure 17 for a photograph of the PMD). Briefly, we have used two variations of a transfer design to determine whether infants actually learn the contingency between pulling on the joystick and moving in the PMD. In both designs, infants are initially placed in the PMD (in either a prone position or a seated position) for a 5-min period and observed to determine the frequency and duration with which they pull on a single joystick. (The PMD can be set to follow a linear path toward the mother or a circular trajectory around the mother when the joystick is pulled.) Following a 3-min rest, the infants are again placed in the PMD for a 5-min period under one of two conditions. In the first condition, the single joystick is either active or inactivated, and in the second, an additional, inactive, joystick is added.

The data for a sample of 8 infants during the second 5-min period of the design in which an additional inactive joystick is added (note that the position of the active joystick, right or left side, is counterbalanced across infants) are presented in Figure 18. In this particular design, the infants are in a prone position, and as noted earlier, move in a circular trajectory around the mother. The data show clearly that the infants spend a much greater proportion of time pulling on the active as opposed to the inactive joystick. This finding suggests that infants were not simply motivated to pull a joystick but were motivated to pull a joystick that would lead to forward motion in the PMD.

Based on the Anderson et al. (1999) results, we are very encouraged that the consequences of locomotor experience can be tested in a true experiment. One might wonder why we chose to manipulate locomotor experience in a PMD at this time rather than to train infants to crawl, as was done by Lagerspetz et al. (1971). A crawling manipulation certainly has ecological validity, however, given the drastic changes in the family ecology following the onset of crawling, many parents are disinclined to want a precocious crawler. Furthermore, the PMD has several advantages over a crawling manipulation. First, it is less cumbersome and time consuming

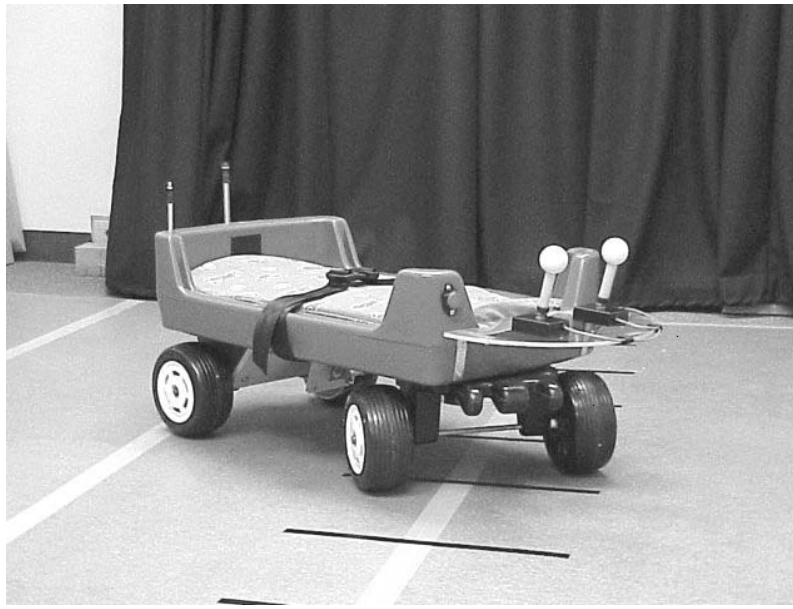

FIGURE 17 Photograph of the powered mobility device used in the Anderson, Campos, Barbu-Roth, and Uchiyama (1999) study.

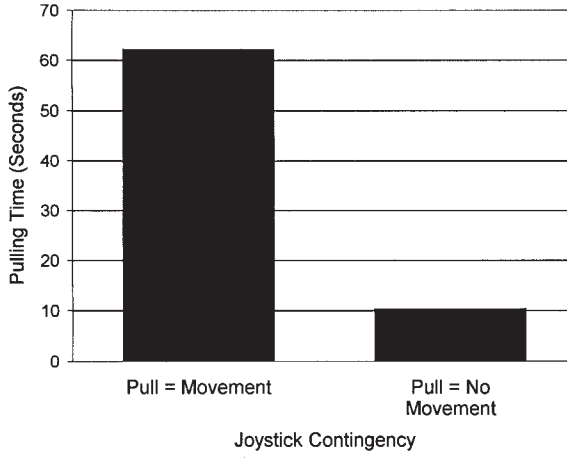

FIGURE 18 Time spent pulling the active and inactive joystick during the second 5-min period of the transfer design used by Anderson et al. (1999).

on the infant and the experimenter—our data are quite clear in showing that most infants learn to control their motion in the PMD relatively quickly. Related to this point, learning to locomote in the PMD is much less effortful and attention demanding than learning to crawl, freeing the infant to attend to the environment and its characteristic patterns of change during the course of locomotion.

Perhaps the greatest advantage of the PMD paradigm, though, is the ability to run a yoked-control design, similar to the classic Held and Hein (1963) experiment in which one infant receives active locomotor experience and another receives the same locomotion passively. We intend to perform such a study with monozygotic twins to control for maturational changes that can be involved in developmental changes relevant to our interests. Using such a design the researcher can tease apart the role of locomotion per se from the role of self (in the genesis of behavior) on changes in the developmental phenomena that have been chronicled in this article. We predict that the developmental changes described in this article are critically dependent on self-produced locomotion rather than locomotion in general. A twin design is also one of the few means available to the researcher on human infants to tease apart the role of genetics and environment on psychological development. A twin study crossing the factors of heredity with type of movement is clearly called for to study the role of gene–environment interaction. Such a study involves comparing monozygotic and dizygotic twins, some of whom are given active and some given passive movement experience. Such an investigation is one of the most sensitive means we can think of to assess the separate and conjoint influences of genes and experience on the psychological outcomes we described.

CONCLUSIONS

The foregoing review clarifies that the onset of crawling heralds major changes in the psychology of the child. We present a summary of the findings from the work we conducted in our laboratory in Table 1, along with the converging research operations used to determine how consistent the link is between locomotor experience and psychological consequences. However, does this empirical work, with the conceptualizations that it has engendered, have broader implications than documenting that crawling experience is important during a rather narrow age range? Do the phenomena delineated in this article have long-lasting consequences for the infant? Are there major conceptual lessons to be learned that transcend this highly constrained phenomenon? Are there analogous events earlier or later in life that, like crawling onset, have major unanticipated or uninvestigated sequelae? We believe that the answer to these questions is an emphatic “yes,” and we delineate some of these broad implications in the final section of the article.

TABLE 1
Summary of Our Findings Linking Locomotor Experience to Psychological Functions

	How Demonstrated						
Consequences of Locomotor Experience	*A*	*B*	*C*	*D*	*E*	*F*	*How Locomotor Experience Brings About Psychological Change*
Changes in family social dynamics	+	–				+	Increase in infant autonomy → need for infant autonomy vs. caregiver regulation
Referential gestural communication	+	+		+	+	+	Increased opportunities to relate objects and events to parental communication
Wariness of heights	+	+	+	+	+	+	Reaction to discrepancy between visual and vestibular information specifying self-motion
Postural compensation to peripheral optic flow	+	+					Differentiation of regions of optic flow for efficient control of locomotion
Attention to far space	+	+					Distal events become attainable and so increasingly functional
Spatial search performance	+	+	+	+	+	+	Use of strategies like “keeping an eye” on target Discrimination of relevant environmental features Locomotion requires new coding strategies Longer locomotor excursions lead to tolerance of longer delays in goal attainment Improved understanding of others’ intentions
Spatial coding strategies	+	+		+			Environmental-referent strategies are problematic for prelocomotor infants

Note. A = locomotor vs. prelocomotor; B = walker vs. prelocomotor; C = lag-sequential; D = Locomotor Delay (neurological/orthopedic); E = locomotor delay (ecological); F = longitudinal; + = positive findings; – = predicted relation not confirmed.

When asked what makes a phenomenon important, most developmentalists would emphasize whether events early in life are successful in forecasting later characteristics. Indeed, the study of child development is largely the study of predictors of later personality, intelligence, social characteristics, and brain function. Viewed in this way, the research on the correlates and consequences of crawling can seem modest in scope and significance. And indeed, we are not claiming that individual differences in the age of onset of a motoric skill predict future intelligence or emotionality. No one has ever documented such a predictive link. So, have we just finished an article with only a narrow focus?

We believe not and argue that locomotor experience might well have enduring consequences, but of a vastly different nature than those focused on typically by developmentalists. The long-term significance of locomotor experience is that once attained, it is typically maintained. Except under extraordinary circumstances, once a child begins to locomote, crawling, walking, running, and other forms of moving about produce a constant developmental framework. This framework helps to maintain skills that locomotor experience helped to generate in the first place, and often require recurrent updating and pervasive maintenance. Viewed in this way, locomotor experiences can have far more enduring significance than most, if not all, of the phenomena that developmentalists typically study. In short, developmentalists often talk of "scaffolding" as a needed or helpful short-term support for development; locomotor experience is more than a scaffold. It is like the supporting frame of a building, always necessary for the building's integrity. If this analogy is correct, research needs to be conducted on what occurs when locomotor experience becomes unavailable to the human. What occurs in the psychological states of the person who, by reason of lesion or illness, loses locomotor ability and experience? It is noteworthy that we know of no research on this topic.

There is a second broad implication to the work we described. It forces a different view of the processes by which development takes place. Notice that in almost every phenomenon we discussed, crawling brings about developmental change by recruiting processes that are available in ways other than by locomoting. For example, attention to distal events, use of parallax information, social interactions involving referential communication, and differential attentiveness to new affordances of events in the world can and doubtless do occur even when the child is unable to crawl. The significance of locomotion is in making the operation of such processes almost inevitable. However, the process analyses we described also make efforts to understand alternative developmental pathways equally inevitable.

The processes of developmental change can also be quite independent of each other. The factors that account for the flowering of the child's affectivity following locomotor onset are dramatically different from those that enter into the shifts in successful search following a delay, those related to spatial cognition, or those

linked to improvements in distance estimation. Even within the domain of affective development, the processes that bring about fear of heights differ from those that produce anger and frustration, or for that matter, fears of animals and insects "caught" from the mother.

If we are correct in construing how locomotion brings about psychological changes, we will also need to begin viewing development in probabilistic rather than fixed ways. We are proposing that development involves the orchestration of processes to bring about new levels of psychological function. The best illustration of the orchestration principle in the studies we described involves the explanation of the wariness of heights phenomenon. Fear of heights is not just the outcome of depth perception. If depth perception alone generated avoidance of heights, 5-month-old infants would show wariness of heights and they do not (Schwartz, Campos, & Baisel, 1973). The avoidance of drop-offs results from the development, first of increased responsiveness to peripheral optic flow, second from the mismatches with vestibular input that such new responsiveness makes possible, and third, the vertigo or sense of postural instability that the mismatch engenders. Development of phenomena like wariness of heights cannot be explained in monistic terms (e.g., as due to "depth perception," or the maturation of the frontal lobes, or falling experiences). Development involves organizing (orchestrating) many component processes into more and more complex levels. We have illustrated the process of orchestration and showed how each domain involves the interplay of different segments of experience. We have also shown how a relatively neglected developmental event—locomotor experience—plays the role of an organizer or orchestrator. In so doing, we hope we have shown how fruitful it is to conceptualize a variety of enduring psychological changes in ways that are both domain specific and yet under a single agent of control.

So, locomotor experience has effects that can be enduring, even though they are not necessarily predictive of the future; locomotor experience also can explain developmental transitions, even though it cannot determine them; and locomotor experience dramatically changes the relation of the person to that person's environment. This last point is particularly broad and heuristic. It highlights the importance of studying any life event that changes the relation between the person and the environment. The more profoundly the developmental acquisition changes such relations, the more significant is that life event, and the richer that age period is for a developmental analysis of how the life event results in psychological changes.

There are many life events likely to have major consequences for person–environment reorganizations in infancy. Some are motoric; others are not. The motoric attainments with developmental implications include the experiences made possible by reaching and those by upright locomotion. Neither has been studied systematically or even extensively, although Witherington (1998) and Biringen et al. (1995) began to study the correlates and consequences of reaching and walking, respectively. A nonmotoric attainment—learning to speak—is yet another life

event with profound psychological consequences (Bloom, 1993). Although language acquisition is a major area of investigation, few of the myriad studies in the area have focused on the consequences of language acquisition for other psychological characteristics. Surely, the changes following language onset must be as pervasive and profound as those discovered to date for crawling. A major implication of the work described in this article is the analogy that it provides for conceptualizing and investigating other periods of rapid developmental transition in infancy and early childhood.

Our language often systematizes in the form of idiomatic expressions major aspects of our lives. Lakoff and Johnson (1980) referred to these as "metaphors we live by." Perhaps it is no accident that we have idioms such as "making great strides," "step-function improvement," and "moving ahead" to refer to accomplishments. Locomotion connotes progress and advance, in the person's relation to the environment and in the person's mind. In this article, we tried to make a case for invigorating the investigation of the role of motoric attainments for psychological development. Such investigations of functional consequences of motor-skill acquisition have been seriously neglected. We maintain that the neglect has been brought about by inappropriate beliefs, of which three stand out. One is the confusion of partial accomplishments with full-blown skills; a second is the restricted way of construing how events can have long-term significance; the third is an overemphasis on single-factor explanations of development. We hope that this article provided evidence against each of these beliefs, and that the developmentalist's typical concern with origins and long-term outcomes can be supplemented again by the currently unfashionable study of developmental transitions in infancy. The rejuvenation of concern with transitions and the processes by which they come about can be the most valuable legacy of the study of locomotor experience in infancy.

ACKNOWLEDGMENTS

Preparation of this article was supported by the following: Joseph J. Campos was supported by the following grants: National Institutes of Health (NIH) grant HD-25066, a grant from the John D. and Catherine T. MacArthur Foundation, National Science Foundation (NSF) grant SBR-9116151, and a Fellowship from the Center for Advanced Study in the Behavioral Sciences. David I. Anderson was supported by a Research Infrastructure in Minority Institutions award from the National Center for Research Resources with funding from the Office of Research on Minority Health, NIH grant RR11805-02, NIH grant HD-36795, and NSF grant SBR-9116151. Marianne A. Barbu-Roth was supported by the Centre National de la Recherche Scientifique in France. Matthew J. Hertenstein was supported by a National Research Service Award predoctoral fellowship MH-12320. David

Witherington was supported by an NIH predoctoral training grant, HD-07181 and an NIH postdoctoral training grant, HD-07323.

We thank Professor Ichiro Uchiyama for contributing to discussions about the ideas contained herein, and Dr. Diane Spitler-Anderson and Tabatha Thomas for helpful comments on drafts of this article.

Unpublished materials referred to in this article can be obtained from Joseph J. Campos.

REFERENCES

Acredolo, L. P. (1978). Development of spatial orientation in infancy. *Developmental Psychology, 14,* 224–234.

Acredolo, L. P. (1979). Laboratory versus home: The effect of environment on the 9-month-old infant's choice of spatial-reference system. *Developmental Psychology, 15,* 666–667.

Acredolo, L. P. (1982). The familiarity factor in spatial research. *New Directions for Child Development, 15,* 19–30.

Acredolo, L. P. (1985). Coordinating perspectives on infant spatial orientation. In R. Cohen (Ed.), *The development of spatial cognition* (pp. 115–140). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Acredolo, L. P., Adams, A., & Goodwyn, S. W. (1984). The role of self-produced movement and visual tracking in infant spatial orientation. *Journal of Experimental Child Psychology, 38,* 312–327.

Acredolo, L. P., & Evans, D. (1980). Developmental changes in the effects of landmarks on infant spatial behavior. *Developmental Psychology, 16,* 312–318.

Adolph, K. E., Vereijken, B., & Denny, M. A. (1998). Learning to crawl. *Child Development, 69,* 1299–1312.

Ainsworth, M. S., Blehar, M. C., Waters, E., & Wall, S. (1978). *Patterns of attachment: A psychological study of the strange situation*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Anderson, D. I., Campos, J. J., Barbu-Roth, M. A., & Uchiyama, I. (1999, June). *Motor behavior and psychological function.* Paper presented at the North American Society for the Psychology of Sport and Physical Activity, Clearwater Beach, FL.

Arterberry, M., Yonas, A., & Bensen, A. S. (1989). Self-produced locomotion and the development of responsiveness to linear perspective and texture gradients. *Developmental Psychology, 25,* 976–982.

Bai, D. L., & Bertenthal, B. I. (1992). Locomotor status and the development of spatial search skills. *Child Development, 63,* 215–226.

Banks, M. S. (1988). Visual recalibration and the development of contrast and optical flow perception. In A. Yonas (Ed.), *Perceptual development in infancy* (pp. 145–196). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Bayley, N. (1969). *Manual for the Bayley scales of infant development.* New York: Psychological Corporation.

Berkeley, G. (1709). *An essay towards a new theory of vision* (2nd ed.). Dublin, Ireland: Aaron Rhames for Jeremy Pepyat.

Bertenthal, B. I. (1990). Application of biomechanical principles to the study of perception and action. In H. Bloch & B. I. Bertenthal (Eds.), *Sensory-motor organizations and development in infancy and early childhood* (pp. 243–260). Dordrecht, Netherlands: Kluwer Academic.

Bertenthal, B. I., & Bai, D. L. (1989). Infants' sensitivity to optical flow for controlling posture. *Developmental Psychology, 25,* 936–945.

Bertenthal, B. I., & Campos, J. J. (1984). A reexamination of fear and its determinants on the visual cliff. *Psychophysiology, 21,* 413–417.

Bertenthal, B. I., & Campos, J. J. (1990). A systems approach to the organizing effects of self-produced locomotion during infancy. In C. Rovee-Collier & L. P. Lipsitt (Eds.), *Advances in infancy research* (Vol. 6, pp. 1–60). Norwood, NJ: Ablex.

Bertenthal, B. I., Campos, J. J., & Barrett, K. C. (1984). Self-produced locomotion: An organizer of emotional, cognitive, and social development in infancy. In R. Emde & R. Harmon (Eds.), *Continuities and discontinuities in development* (pp. 175–210). New York: Plenum.

Bertenthal, B. I., & Clifton, R. (1998). Perception and action. In D. Kuhn & R. Siegler (Eds.), *Cognition, perception and language* (Vol. 2, 5th ed., pp. 51–102). New York: Wiley.

Bertenthal, B. I., Rose, J. L., & Bai, D. L. (1997). Perception-action coupling in the development of visual control of posture. *Journal of Experimental Psychology: Human Perception & Performance, 23,* 1631–1643.

Beryl, F. (1926). Uber die Grossenauffasung bei Kindern [On the size perception of young children]. *Zeitschrift fur Psychologie, 100,* 344–371.

Biringen, Z., Emde, R. N., Campos, J. J., & Appelbaum, M. I. (1995). Affective reorganization in the infant, the mother, and the dyad: The role of upright locomotion and its timing. *Child Development, 66,* 499–514.

Bloom, L. (1993). *The transition from infancy to language: Acquiring the power of expression.* New York: Cambridge University Press.

Bowlby, J. (1969). *Attachment and loss: Attachment*. New York: Basic Books.

Brandt, T., Bles, W., Arnold, F., & Kapteyn, T. S. (1979). Height vertigo and human posture. *Advances in Oto-rhino-otolaryngology, 25,* 88–92.

Bremner, J. G. (1978). Egocentric versus allocentric spatial coding in 9-month-old infants: Factors influencing the choice of code. *Developmental Psychology, 14,* 346–355.

Bremner, J. G. (1985). Object tracking and search in infancy: A review of data and a theoretical evaluation. *Developmental Review, 5,* 371–396.

Bremner, J. G. (1993a). Motor abilities as causal agents in infant cognitive development. In G. J. P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 47–77). Amsterdam, Netherlands: Elsevier Science.

Bremner, J. G. (1993b). Spatial representation in infancy and early childhood. In C. Pratt & A. F. Garton (Eds.), *Systems of representation in children: Development and use* (pp. 67–89). Chichester, England: Wiley.

Bremner, J. G., & Bryant, P. E. (1977). Place versus response as the basis of spatial errors made by young infants. *Journal of Experimental Child Psychology, 23,* 162–171.

Bremner, J. G., & Bryant, P. E. (1985). Active movement and development of spatial abilities in infancy. In H. M. Wellman (Ed.), *Children's searching: The development of search skill and spatial representation* (pp. 53–72). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Butterworth, G., & Hicks, L. (1977). Visual proprioception and postural stability in infancy: A developmental study. *Perception, 6,* 255–262.

Campos, J. J., Benson, J., & Rudy, L. (1986, April). *The role of self-produced locomotion in spatial behavior.* Paper presented at the International Conference of Infant Studies, Beverly Hills, CA.

Campos, J. J., Bertenthal, B. I., & Kermoian, R. (1992). Early experience and emotional development: The emergence of wariness of heights. *Psychological Science, 3,* 61–64.

Campos, J. J., Hiatt, S., Ramsay, D., Henderson, C., & Svejda, M. (1978). The emergence of fear on the visual cliff. In M. Kewis & L. Rosenblum (Eds.), *The development of affect* (pp. 149–182). New York: Plenum.

Campos, J. J., Kermoian, R., Witherington, D., Chen, H., & Dong, Q. (1997). Activity, attention, and developmental transitions in infancy. In P. J. Lang & R. F. Simons (Eds.), *Attention and orienting: Sensory and motivational processes* (pp. 393–415). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Campos, J. J., Kermoian, R., & Zumbahlen, M. R. (1992). Socioemotional transformations in the family system following infant crawling onset. In N. Eisenberg & R. A. Fabes (Eds.), *Emotion and its regulation in early development* (pp. 25–40). San Francisco: Jossey-Bass.

Campos, J. J., & Stenberg, C. (1981). Perception, appraisal, and emotion: The onset of social referencing. In M. Lamb & L. Sherrod (Eds.), *Infant social cognition: Empirical and theoretical considerations* (pp. 274–313). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Churcher, J., & Scaife, M. (1982). How infants see the point. In G. E. Butterworth & P. Light (Eds.), Social cognition: Studies of the development of understanding (pp. 110–136). Sussex, England: Harvester.

Corkum, V., & Moore, C. (1998). The origins of joint visual attention in infants. *Developmental Psychology, 34,* 28–38.

Cornell, E. H., & Heth, C. D. (1979). Response versus place learning by human infants. *Journal of Experimental Psychology: Human Learning & Memory, 5,* 188–196.

Cornilleau-Pérès, V., & Gielen, C. C. A. M. (1996). Interactions between self-motion and depth perception in the processing of optic flow. *Trends in Neurosciences, 19,* 196–202.

Crowell, J. A., & Banks, M. S. (1993). Perceiving heading with different retinal regions and types of optic flow. *Perception & Psychophysics, 53,* 325–337.

Cutting, J. E. (1986). The shape and psychophysics of cinematic space. *Behavior Research Methods, Instruments & Computers, 18,* 551–558.

Day, R. H. (1987). Visual size constancy in infancy. In B. E. McKenzie & R. H. Day (Eds.), *Perceptual development in early infancy: Problems and issues* (pp. 67–91). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Decarie, T. (1969). A study of the mental and emotional development of the thalidomide child. In B. Foss (Ed.), *Determinants of infant behavior* (Vol. 4, pp. 167–187). London: Methuen.

D'Entremont, B., Hains, S. M. J., & Muir, D. W. (1997). A demonstration of gaze following in 3- to 6-month-olds. *Infant Behavior and Development, 20,* 569–572.

Diamond, A. (1991). Neuropsychological insights into the meaning of object concept development. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition* (pp. 67–110). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Dichgans, J., & Brandt, T. (1974). The psychophysics of visually induced perception of self-motion and tilt. In F. O. Schmidt & F. G. Worden (Eds.), *The neurosciences* (Vol. III, pp. 123–129). Cambridge, MA: MIT Press.

Emde, R. N., Gaensbauer, T. J., & Harmon, R. J. (1976). Emotional expression in infancy: A biobehavioral study. *Psychological Issues, 10*(1, Whole No. 34).

Enderby, S. F. (1984). *The effects of self-produced locomotion on the development of spatial orientation in infancy.* Unpublished honors thesis, University of Denver, Denver, CO.

Field, J. (1975, May). *The adjustment of reaching behavior to object distance in early infancy.* Paper presented at the Second Experimental Psychology Conference, Sydney, Australia.

Fischer, K., & Biddell, T. (1998). Dynamic development of psychological structures in action and thought. In R. Lerner (Ed.), *Theoretical models of human development* (Vol. 1, pp. 467–562). New York: Wiley.

Freedman, D. L. (1992). *Locomotor experience and the deployment of attention to near and distant space.* Unpublished honors thesis, University of California, Berkeley.

Gentile, A. M. (1987). Skill acquisition: Actions, movements, and neuromotor processes. In J. H. Carr & R. B. Shepherd (Eds.), *Movement science: Foundations for physical therapy in rehabilitation* (pp. 93–154). Rockville, MD: Aspen.

Gibson, E. J. (1969). *Principles of perceptual learning development.* Englewood Cliffs, NJ: Prentice Hall.

Gibson, E. J., & Schmuckler, M. A. (1989). Going somewhere: An ecological and experimental approach to development of mobility. *Ecological Psychology, 1,* 3–25.

Gibson, J. J. (1966). *The senses considered as perceptual systems.* Boston: Houghton Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Glicksman, M. (1987). The relation between locomotor experience and spatial knowledge in infancy. In P. Ellen & C. Thinus-Blanc (Eds.), *Cognitive processes in spatial orientation in animal and man:*

Vol. 1. Experimental animal psychology and ethology (pp. 264–273). Dordrecht, Netherlands: Martinus Nijhoff.

Goodale, M. A. (1988). Hemispheric differences in motor control. *Behavioural Brain Research, 30,* 203–214.

Gottleib, G. (1991). Experiential canalization of behavioral development: Theory. *Developmental Psychology, 27,* 4–13.

Granrud, C. E. (1986). Binocular vision and spatial perception in 4- and 5-month-old infants. *Journal of Experimental Psychology: Human Perception & Performance, 12,* 36–49.

Granrud, C. E., Haake, R. J., & Yonas, A. (1985). Infants' sensitivity to familiar size: The effect of memory on spatial perception. *Perception and Psychophysics, 37,* 459–466.

Granrud, C. E., & Yonas, A. (1984). Infants' perception of pictorially specified interposition. *Journal of Experimental Child Psychology, 37,* 500–511.

Guedry, F. E. (1974). Psychophysics of vestibular sensation. In H. H. Kornhuber (Ed.), *Handbook of sensory physiology: Vestibular system, part 2: Psychophysics, applied aspects, and general interpretations* (pp. 3–154). Berlin: Springer-Verlag.

Gustafson, G. E. (1984). Effects of the ability to locomote on infants' social and exploratory behaviors: An experimental study. *Developmental Psychology, 20,* 397–405.

Haber, R. N. (1980). How we perceive depth from flat pictures. *American Scientist, 68,* 370–380.

Haith, M. M. (1990). Progress in the understanding of sensory and perceptual processes in early infancy. *Merrill-Palmer Quarterly, 36,* 1–26.

Haith, M. M. (1993). Preparing for the 21st century: Some goals and challenges for studies of infant sensory and perceptual development. *Developmental Review, 13,* 354–371.

Hayashibe, K. (1991). Reversals of depth caused by motion parallax. *Perception, 2,* 17–28.

Hein, A., Held, R., & Gower, E. C. (1970). Development and segmentation of visually controlled movement by selective exposure during rearing. *Journal of Comparative and Physiological Psychology, 73,* 181–187.

Held, R., & Hein, A. (1963). Movement-produced stimulation in the development of visually guided behavior. *Journal of Comparative and Physiological Psychology, 56,* 872–876.

Higgins, C. I. (1994). *The origins of visual proprioception.* Unpublished doctoral dissertation, University of California, Berkeley.

Higgins, C. I., Campos, J. J., & Kermoian, R. (1996). Effect of self-produced locomotion on infant postural compensation to optic flow. *Developmental Psychology, 32,* 836–841.

Holway, A. H., & Boring, E. G. (1941). Determinants of apparent visual size with distance variant. *American Journal of Psychology, 54,* 21–37.

Horobin, K., & Acredolo, L. (1986). The role of attentiveness, mobility history, and separation of hiding sites on Stage IV search behavior. *Journal of Experimental Child Psychology, 41,* 114–127.

Johansson, G. (1973). Monocular movement parallax and near-space perception. *Perception, 2,* 135–146.

Jouen, F. (1988). Visual-proprioceptive control of posture in newborn infants. In B. Amblard, A. Berthoz, & F. Clarac (Eds.), *Posture and gait: Development, adaptation and modulation* (pp. 59–65). Amsterdam: Elsevier Science.

Jouen, F. (1990). Early visual-vestibular interactions and postural development. In H. Bloch & B. I. Bertenthal (Eds.), *Sensory-motor organizations and development in infancy and early childhood* (pp. 199–215). Dordrecht, Netherlands: Martinus Nijhoff.

Jouen, F., & Gapenne, O. (1995). Interactions between the vestibular and visual systems in the neonate. In P. Rochat (Ed.), *The self in infancy: Theory and research* (pp. 277–301). Amsterdam, Netherlands: Elsevier Science.

Kagan, J., Kearsley, R. B., & Zelazo, P. R. (1978). *Infancy: Its place in human development*. Cambridge, MA: Harvard University Press.

Kaufman, L. (1974). *Sight and mind: An introduction to visual perception*. New York: Oxford.

Kermoian, R., & Campos, J. J. (1988). Locomotor experience: A facilitator of spatial-cognitive development. *Child Development, 59,* 908–917.

Koenderink, J. J. (1999). *Pictorial relief.* Paper presented at the Oxyopia symposium, University of California, Berkeley.

Kopp, C. B., & Shaperman, J. (1973). Cognitive development in the absence of object manipulation during infancy. *Developmental Psychology, 9,* 430.

Lagerspetz, K., Nygård, M., & Strandvik, C. (1971). The effects of training in crawling on the motor and mental development of infants. *Scandanavian Journal of Psychology, 12,* 192–197.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by.* Chicago: University of Chicago Press.

Lazarus, R. S. (1991). *Emotion and adaptation.* New York: Oxford University Press.

Lee, D. N., & Aronson, E. (1974). Visual proprioceptive control of standing in human infants. *Perception and Psychophysics, 15,* 529–532.

Lee, D. N., & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies, 1,* 87–95.

Leibowitz, H. W., & Post, R. B. (1984). The two modes of processing concept and some implications. In J. Beck (Ed.), *Organization and representation in perception* (pp. 343–363). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Lepecq, J.-C. (1990). Self-produced movement, position constancy, and the perceptual-learning approach. In H. Bloch & B. I. Bertenthal (Eds.), *Sensory-motor organizations and development in infancy and early childhood* (pp. 445–453). Dordecht, Netherlands: Kluwer Academic.

Lepecq, J.-C., & Lafaite, M. (1989). The early development of position constancy in a no-landmark environment. *British Journal of Developmental Psychology, 7,* 289–306.

Mahler, M. S., Pine, F., & Bergman, A. (1975). *The psychological birth of the human infant: Symbiosis and individuation.* New York: Basic Books.

Mayne, R. (1974). A systems concept of the vestibular organs. In H. H. Kornhuber (Ed.), *Handbook of sensory physiology: Vestibular system, part 2: Psychophysics applied aspects, and general interpretations* (pp. 493–580). Berlin: Springer-Verlag.

McComas, J., & Field, J. (1984). Does crawling experience affect infants' emerging spatial orientation abilities? *New Zealand Journal of Psychology, 13,* 63–68.

McKenzie, B. E. (1987). The development of spatial orientation in human infancy: What changes? In B. E. McKenzie & R. H. Day (Eds.), *Perceptual development in early infancy: Problems and issues* (pp. 125–142). Hillsdale: NJ: Lawrence Erlbaum Associates, Inc.

McKenzie, B. E., & Day, R. H. (1972). Object distance as a determinant of visual fixation in early infancy. *Science, 178,* 1108–1110.

McKenzie, B. E., & Day, R. H. (1976). Infants' attention to stationary and moving objects at different distances. *Australian Journal of Psychology, 28,* 45–51.

McKenzie, B. E., Day, R. H., & Ihsen, E. (1984). Localization of events in space: Young infants are not always egocentric. *British Journal of Experimental Psychology, 2,* 1–19.

McKenzie, B. E., Tootell, H. E., & Day, R. H. (1980). Development of visual size constancy during the 1st year of human infancy. *Developmental Psychology, 16,* 163–174.

Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action.* Oxford, England: Oxford University Press.

Moore, C. (1999). Gaze following and the control of attention. In E. P. Rochat (Ed.), *Early social cognition: Understanding others in the first months of life* (pp. 241–256). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Moore, C., & Dunham, P. (1995). *Joint attention: Its origins and role in development.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Munakata, Y. (1998). Infant perseveration and implications for object permanence theories: A PDP model of the A-not-B task. *Developmental Science, 1,* 161–211.

Munakata, Y., McClelland, J. L., Johnson, M. H., & Siegler, R. S. (1997). Rethinking infant knowledge: Toward an adaptive process account of successes and failures in object permanence tasks. *Psychological Review, 104,* 686–713.

Palmer, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: MIT Press.

Piaget, J. (1954). *The construction of reality in the child*. New York: Basic Books.

Piaget, J. (1970). Piaget's theory. In W. Kessen (Ed.), *History, theory, and methods* (pp. 103–126). New York: Wiley.

Rader, N., Bausano, M., & Richards, J. E. (1980). On the nature of the visual-cliff-avoidance response in human infants. *Child Development, 51,* 61–68.

Reed, E. S. (1982). An outline of a theory of action systems. *Journal of Motor Behavior, 14,* 98–134.

Rieser, J. (1979). Spatial orientation of 6-month old infants. *Child Development, 50,* 1078–1087.

Rock, I. (1977). In defense of unconscious inference. In W. Epstein (Ed.), *Stability and constancy in visual perception* (pp. 321–373). New York: Wiley.

Rock, I. (Ed.). (1997). *Indirect perception*. Cambridge, MA: MIT Press.

Rogers, B., & Graham, M. (1979). Motion parallax as an independent cue for depth perception. *Perception, 8,* 125–134.

Rogers, S., & Rogers, B. J. (1992). Visual and nonvisual information disambiguate surfaces specified by motion parallax. *Perception and Psychophysics, 52,* 446–452.

Scarr, S., & Salapatek, P. (1970). Patterns of fear development during infancy. *Merrill-Palmer Quarterly, 16,* 53–90.

Schmuckler, M. A. (1993). Perception-action coupling in infancy. In G. J. P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 137–173). Amsterdam: Elsevier Science.

Schwartz, A. N., Campos, J. J., & Baisel, E. J. (1973). The visual cliff: Cardiac and behavioral responses on the deep and shallow sides at 5 and 9 months of age. *Journal of Experimental Child Psychology, 15,* 86–99.

Shallo, J., & Rock, I. (1988). Size constancy in children: A new interpretation. *Perception, 17,* 803–813.

Shurtleff, D. (Ed.). (1986). *Myelodysplasias and extrophies: Significance, prevention, and treatment.* Orlando, FL: Grune & Stratton.

Slater, A., Mattock, A., & Brown, E. (1990). Size constancy at birth: Newborn infants' responses to retinal and real size. *Journal of Experimental Child Psychology, 49,* 314–322.

Slater, A., & Morison, V. (1985). Shape constancy and slant perception at birth. *Perception, 14,* 337–344.

Smith, L. B., & Thelen, E. (1993). *A dynamic systems approach to development: Applications*. Cambridge, MA: MIT Press.

Smith, L. B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: The task dynamics of the A-not-B error. *Psychological Review, 106,* 235–260.

Stoffregen, T. A. (1985). Flow structure versus retinal location in the optical control of stance. *Journal of Experimental Psychology: Human Perception & Performance, 11,* 554–565.

Stoffregen, T. A. (1986). The role of optical velocity in the control of stance. *Perception and Psychophysics, 39,* 355–360.

Stoffregen, T. A., Schmuckler, M. A., & Gibson, E. J. (1987). Use of central and peripheral optic flow in stance and locomotion in young walkers. *Perception, 16,* 113–119.

Tao, S., & Dong, Q. (1997). *Referential gestural communication and locomotor experience in urban Chinese infants*. Unpublished manuscript, Beijing Normal University, Beijing, China.

Telzrow, R. (1990, April). *Delays and spurts in spatial-cognitive development of the locomotor handicapped infant.* Paper presented at the Annual Meeting of the International Conference on Infant Studies, Montreal, Canada.

Telzrow, R., Campos, J. J., Shepherd, A., Bertenthal, B. I., & Atwater, S. (1987). Spatial understanding in infants with motor handicaps. In K. Jaffe (Ed.), *Childhood powered mobility: Developmental, technical and clinical perspectives* (pp. 62–69). Washington, DC: Rehabilitation Engineering Society of North America.

Telzrow, R. W., Campos, J. J., Kermoian, R., & Bertenthal, B. I. (1999). *Locomotor acquisition as an antecedent of psychological development: Studies of infants with myelodysplasia.* Unpublished manuscript, University of California, Berkeley, CA.

Thomas, D. G., & Crow, C. D. (1988, April). *The effects of self-produced locomotion on depth perception in infants.* Paper presented at the International Conference on Infancy Studies, Washington, DC.

Timney, B. (1988). The development of depth perception. In P. G. Shinkman (Ed.), *Advances in neural and behavioral development* (Vol. 3, pp. 153–208). Norwood, NJ: Ablex.

Trevarthen, C. (1993). The self born in intersubjectivity: The psychology of an infant communicating. In U. Neisser (Ed.), *The perceived self: Ecological and interpersonal sources of self-knowledge* (pp. 121–173). New York: Cambridge University Press.

von Hofsten, C. (1989). Mastering reaching and grasping: The development of manual skills in infancy. In S. A. Wallace (Ed.), *Perspectives on the coordination of movement* (pp. 223–258). Amsterdam: North-Holland.

Walk, R. D., Shepherd, J. D., & Miller, D. R. (1988). Attention and the depth perception of kittens. *Bulletin of the Psychonomic Society, 26,* 248–251.

Wellman, H. M., Cross, D., & Bartsch, K. (1987). Infant search and object permanence: A meta-analysis of the A-not-B error. *Monographs of the Society for Research in Child Development, 51,* 1–51.

Witherington, D. (1998). *Visually guided reaching and the development of anger in infancy.* Unpublished doctoral dissertation, University of California, Berkeley.

Witherington, D., Campos, J. J., & Kermoian, R. (1995, March). *What makes a baby afraid of heights?* Paper presented at the Society for Research in Child Development, Indianapolis, IN.

Wohlwill, J. F. (1963). Overconstancy in distance perception as a function of the texture of the stimulus field and other variables. *Perceptual and Motor Skills, 17,* 831–846.

Woods, T. E. P. (1975). *Locomotor reinforcement of non-nutritive sucking in human infants.* Unpublished master's thesis, San Francisco State University, San Francisco.

Yonas, A., Arterberry, M. E., & Granrud, C. E. (1987). Four-month-old infants' sensitivity to binocular and kinetic information for three-dimensional-object shape. *Child Development, 58,* 910–917.

Yonas, A., & Granrud, C. A. (1985). Reaching as a measure of infants' spatial perception. In G. Gottlieb & N. A. Krasnegor (Eds.), *Measurement of audition and vision in the first year of postnatal life: A methodological overview* (pp. 301–322). Norwood, NJ: Ablex.

Yonas, A., Granrud, C. E., Arterberry, M. E., & Hanson, B. L. (1986). Infants' distance perception from linear perspective and texture gradients. *Infant Behavior and Development, 9,* 247–256.

Yonas, A., Granrud, C. E., & Pettersen, L. (1985). Infants' sensitivity to relative size information for distance. *Developmental Psychology, 21,* 161–167.

Zumbahlen, M. (1997). *The role of infant locomotor onset in shaping mother–infant communication.* Unpublished doctoral dissertation, University of Illinois at Urbana-Champaign, Urbana.

Zumbahlen, M., & Crawley, A. (1997, April). *Infants' early referential behavior in prohibition contexts: The emergence of social referencing.* Paper presented at the invited symposium on social referencing at the Meetings of the International Conference on Infant Studies, Providence, RI.