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Motor Development and the Mind: The Potential Role of Motor Abilities as a Determinant of Aspects of Perceptual Development

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Bushnell, Emily W., and Boudreau, J. Paul. *Motor Development and the Mind: The Potential Role of Motor Abilities as a Determinant of Aspects of Perceptual Development.* Child Development, 1993, **64**, 1005–1021. Recent advances in the science of human movement have enabled developmental psychologists to discover unique patterns of organization and control in infant motor behavior and development, provoking a resurgence of interest in this topic. In this article, we emphasize the role that motor development may play in determining developmental sequences or "timetables" in other domains. Specifically, we argue that particular motor achievements may be integral to developments in the domains of haptic perception and depth perception. In both cases, there is a high degree of fit between the developmental sequence in which certain perceptual sensitivities unfold and the ages at which the corresponding motor abilities onset. The discussions may provide new contexts in which to consider the developments of haptic perception and depth perception. The general purpose, however, is to highlight the wide-ranging influence of motor development during infancy.

Systematic empirical investigation of infant behavior essentially began with the work of Gesell (Gesell, 1933; Gesell & Thompson, 1934) describing normative timetables for infant motor achievements and that of McGraw (McGraw, 1935, 1945) examining the determinants of these patterns. However, the topic of motor development received very little attention during the field of infancy's "coming of age" in the 1960s, 1970s, and early 1980s. Studies of motor development were both heavily outnumbered and strongly overshadowed by intense and productive inquiries into infant perception, socioemotional development, and cognitive development. To document this hiatus, we note that not a single chapter in either the first or second edition of the *Handbook of Infant Development* (Osofsky, 1979, 1987) or in the most recent *Handbook of Child Psychology* (Mussen, 1983) is devoted to motor development. With a few notable exceptions (see Bruner, 1970, 1973; White, Castle, & Held, 1964; Zelazo, Zelazo, & Kolb, 1972), if motor behavior was observed at all during this period, it was observed as a dependent variable in research designed to investigate other areas of infant development. For example, Yonas and Granrud have relied on reaching as a measurable response in their comprehensive program of research on infants' depth perception abilities (for a review, see Yonas & Granrud, 1985c), and Rovee-Collier similarly has relied on leg kicking as a measurable response in her investigations on operant learning and memory during infancy (for a review, see Rovee-Collier & Hayne, 1987).

Recently, however, as this special section in *Child Development* celebrates, there has been a dramatic resurgence of interest in motor development during infancy. For instance, in 1990, program organizers for the International Conference on Infant Studies included for the first time a separate review committee for submissions dealing with aspects of motor development. Perhaps the field took a hint from the unwavering excitement infants themselves have always expressed about their motor achievements; realistically, however, we attribute the current revival to new, molecular-level analyses of infant motor behaviors and to a willingness to challenge traditional explanations of developmental change.

Meticulous observation has long been the hallmark of studying motor development. Early investigations characterized week-to-week changes in infants' abilities

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through laborious frame-by-frame scrutiny of film clips of babies reaching, crawling, and walking (e.g., Burnside, 1927; Gesell, 1928; Halverson, 1931). More recent work has examined motor behaviors in even greater detail, however, focusing on the temporal and spatial aspects of single instances of movement. Computer-assisted, three-dimensional digitizing systems that utilize extremely high sampling rates, such as the prototypical WATSMART and OPTOTRAK systems developed in Waterloo, Ontario, have frequently been useful in these efforts. In the context of developmental research, this approach has led to the identification of both striking invariances and parameters of change that were heretofore obscured. Perhaps the most well-known examples here derive from Esther Thelen's kinematic analyses of young infants' spontaneous and seemingly diffuse leg kickings (Thelen & Fisher, 1983). She found that these leg movements displayed the tight synchrony of hip-knee-ankle flexion and extension and also the constant duration of the "swing" phase over increases in rate that are typical of stepping movements during mature locomotion (walking). These results in turn imply that newborns come equipped with an intrinsic pattern generator for locomotion, and thus that coordinating the activities of the leg's individual joints is *not* a factor in "learning to walk" (Thelen, 1984). In contrast, in analyses of infants' stepping on a treadmill (a circumstance analogous to when prelocomotor infants are "walked" by adults holding their hands or trunk), Thelen and Ulrich (1991) observed improvements in interlimb coordination, with alternating steps becoming the preferred pattern over other couplings with age and/or experience. Thus, consolidating the pattern of alternating the two legs or consistently selecting this pattern over others for the purpose of locomotion may be a factor in achieving independent walking.

In addition to new descriptions of motor behavior and development, new explanations for these patterns have recently been offered. Traditionally, developmental changes in motor abilities were attributed to maturational processes (e.g., myelinization, dendritization) in the central nervous system (McGraw, 1941, 1945). Modifications of standard learning theory, reference to perceptual and social incentives, and information-processing concepts have also been employed in explanations for motor development (Bower, 1974; Bruner, 1973; White et al., 1964; Zelazo, 1976). In any of these prior accounts, motor development is viewed as a derivative of processes and events occurring at some higher or more central level—changes in the "mind" (or brain) of infants effect changes in their abilities to deploy the "body." An approach formulated in physics and biology holds, however, that changes may emerge from or "fall out of" the self-organizing tendencies and constraints among the interacting components in the system itself (see Thelen & Fogel, 1989; Thelen & Ulrich, 1991). Some researchers have turned to this "dynamic systems" approach as a more adequate account for many aspects of early motor development. Again, the most vivid illustrations of this novel approach come from Thelen's work. She argues, for example, with considerable and very clever evidence, that stepping behavior in young infants "disappears" in the second or third month simply because their legs increase in mass much more than they gain in strength during the first months of life (Thelen, Fisher, & Ridley-Johnson, 1984). Similarly, she proposes that independent walking in humans begins as late as it does (compared with other species and other forms of self-locomotion) because infants' relatively heavy heads and short legs make balance excessively difficult for them. Thus, in this view, motor development is not seen as "programmed" or as a consequence of developments in other domains. Instead, it proceeds on account of adjustments and reorganizations of components intrinsic to the functioning motor system itself; these must therefore be examined in their own right.

In this article, we aim to take this legitimating of motor development one step farther. We will emphasize that the emergence of particular motor abilities may actually determine some aspects of perceptual and cognitive development, rather than the other way around. The importance of motor activity to perceptual and cognitive development has already been acknowledged in developmental psychology, of course. A main tenet of Piaget's theory of intelligence is that representational thought evolves from overt activities with objects during infancy (Piaget, 1952, 1954), and the dynamic interplay between acting and perceiving is central to the Gibsonian perspective on perception and perceptual development (E. J. Gibson, 1982; J. J. Gibson, 1979). Empirically, a number of investigations have focused on the propensities of infants to coordinate their actions with concurrent perceptual information and feedback in the execution of behaviors such as localizing sounds, reaching, and maintaining their balance (e.g., Lee & Aronson, 1974; McDonnell & Abraham, 1979; Muir & Field, 1979; see Lockman, 1990, for a review). Such "on-line" interactions between motor activity and perception and cognition are interesting and important; however, what we hope to highlight here is the part that motor development may play in determining developmental *sequences* or "timetables" in other domains.

Development in virtually any domain is typically described as a progression of "stages" through which the infant advances, with one stage giving way to the next when certain skills or methods of operating (often incomplete or imprecise) are replaced or augmented by others (usually more effective). A central task for developmental psychologists is to first identify and then account for these progressions. Why does a given ability characteristically emerge *before* or *after* certain other abilities in the course of development? Currently, the notion of constraint or of a "brake" on development (Harris, 1983) is often invoked to explain developmental sequences. The idea here is that either the acquisition or the practice of a particular ability may *entail* other abilities or developmental achievements; thus, the particular ability cannot emerge if any of the capacities it entails is lacking, and therefore the particular ability would *follow* the entailed capacities in the developmental timetable. For example, infants do not recognize their mothers' faces until about 4 months of age *not* because of anything to do with the dynamics of their relationships with their mothers, but because up to that time, their visual acuity (contrast sensitivity) is too poor to resolve the mother's face as distinct from other faces. Thelen's argument mentioned earlier that 2–3-month-old infants do not exhibit stepping because their leg muscles do not have the requisite strength to counteract gravity is another example of this reasoning.

In what follows, the notion of constraint is employed to illustrate how motor development may determine the sequence in which certain perceptual and cognitive abilities unfold. The general line of argument is that if an infant is unable (for whatever developmental reason) to engage in a motor behavior that is requisite to the acquisition or practice of a certain perceptual or cognitive capacity, then that motor failing may block the emergence of the related perceptual or cognitive capacity. The point in development when the motor skill in question emerges will serve as a lower bound for when the perceptual or cognitive capacity might emerge. In the language of the dynamic systems approach, motor development itself may serve as a "control parameter" within the larger system of the whole developing organism.

The potential impact of motor development on the emergence of abilities in other domains has already been recognized in the case of two key motor "milestones" achieved during infancy. Perhaps the most dramatic and elementary example involves the onset of self-generated locomotion (creeping, crawling, or walking). Bertenthal, Campos, and Barrett (1984) have argued persuasively that the onset of self-generated locomotion is functionally related to a wide variety of developmental changes that occur during the second half year of life. The changes affected include perceptual-cognitive ones, such as the shift toward coding locations in terms of landmarks instead of in terms of the self, and also social-emotional ones, such as the emergence of the ability and tendency to engage in social referencing. The crux of Bertenthal et al.'s argument is the idea that becoming mobile serves as a "setting event"—it vastly increases the likelihood and salience of certain experiences for the infant; these experiences in turn facilitate, necessitate, or provoke the developmental changes in question. The proposed determining role of self-generated locomotion is supported with some intriguing empirical evidence. For example, both infants who had begun to crawl on their own and infants who had experience locomoting in wheeled walkers relied on landmarks to code spatial location more frequently than infants of the same age who neither crawled nor used walkers.

The other motor achievement that has been identified as possibly integral to developments in other domains is the mastery of visually guided reaching. The ability to obtain seen objects certainly expands and alters the scope of an infant's experiences in the same sense that self-generated locomotion does. More specifically, Bushnell (1985) has pointed out that an act of prehension is nearly always involved in the interactions with objects that Piaget considered important to an infant's understanding of object permanence, cause-effect relationships, and spatial concepts such as containment. Bushnell suggested that the attainment of such cognitive milestones might be inhibited during the period when reaching is an emerging rather than a well-practiced skill, because just coordinating the reach with the object's location in visual space fully occupies the infant's attention. This line of reasoning now needs qualification, in light of recent findings indicating that infants as young as 3½ months of age can visually distinguish events that are inconsistent with object permanence (Baillargeon, 1987; Baillargeon, Spelke, & Wasserman, 1985). Perhaps the automaticizing of reaching that Bushnell emphasized enables the cognitive advance that permits 8- or 9-month-old infants to act upon their knowledge of objects as they do in traditional search tasks.

Although some researchers are now beginning to consider the implications of postural achievements such as self-sitting (Fogel, 1992; Rochat & Senders, 1990), self-locomotion and hand-eye coordination are the only motor achievements to date whose influence on developments in other domains has been seriously analyzed. Perhaps this is because the limitations imposed by not being able to move from place to place and by not being able to obtain and wield objects with the hands are rather transparent. In the remainder of this article, we will work through two additional instances in which aspects of motor development may determine other developmental timetables. The cases we will describe both involve multiple-step sequences in perceptual development. They also involve motor achievements more subtle or "microscopic" than gross milestones such as crawling and reaching. The discussions may provide new contexts in which to consider the developments of haptic perception and depth perception during infancy. The general purpose, however, is to highlight the wide-ranging influence of motoric limitations in early development.

Before proceeding into the details of the two sequences to be related to motor development, we must acknowledge a concern in the analysis of virtually any developmental sequence. The issue arises from the fact that particular skills and abilities do not suddenly appear fully formed in a child's behavioral repertoire. Instead, they conform to the principle of "developmental gradualness" (Fischer & Bidell, 1992), appearing initially in rudimentary forms and in highly specific contexts, and then gradually becoming more complex and wide-ranging over time. Even seemingly singular achievements such as independent sitting and walking can be seen upon close examination to undergo protracted courses of development. This epigenetic or "unfolding" quality of development makes it difficult to establish a particular ability's precise time of onset during infancy or childhood, which in turn makes it difficult to order the onsets of different skills with respect to one another, as befits our purpose here. We find some reassurance in the fact that the various age norms and onset times incorporated in our arguments all derive from observations of infants' voluntary behavior (rather, e.g., than physiological responses) in quasi-natural situations. Thus, we are presumably tapping into comparable points in the gradual developments of the perceptual and motor abilities in question, and therefore may take the apparent orders of onset as authentic; the case for motor development as a constraint rests on these relations between onset times, which we will now elaborate.

Example 1: The Developmental Course of Haptic Perception

Our first example concerns the development of haptic perception during infancy, a topic on which we have been actively conducting research. Haptic perception refers to the ability to acquire information about objects with the hands, to discriminate and recognize objects from handling them as opposed to looking at them. Interest in infants' haptic perceptual abilities has grown over the last 10 years, evolving initially from investigations focused on cross-modal transfer between vision and touch during infancy (e.g., Bryant, Jones, Claxton, & Perkins, 1972; Bushnell, 1978; Gottfried, Rose, & Bridger, 1977; Rose, Gottfried, & Bridger, 1981). Adaptations of methods employed in research on infants' visual perception have by now yielded a modest empirical literature on infants' haptic abilities.

Recently we undertook to review the literature on infants' haptic abilities in order to identify organizing themes, developmental trends, and remaining issues (Bushnell & Boudreau, 1991). A wide net was cast in considering studies for this review; included were studies designed specifically to assess infants' discrimination of objects by touch alone, studies designed to assess infants' perception of objects across vision and touch (which entails haptic discrimination), and studies designed to examine infants' manual responses to different sorts of objects during naturalistic play (in which haptic perception is accompanied by visual perception). In the review, studies were organized according to the type of stimulus contrast they incorporated; these included the several object properties that are haptically perceivable (i.e., temperature, size, texture, hardness, weight, and shape). Studies employing stimulus objects differing in shape were further subdivided according to the nature of the stimulus difference involved; for reasons outlined in the original review, two studies that used objects differing topologically (e.g., a solid disc vs. a ring) were considered with studies focused on size, and several studies that used objects differing featurally (e.g., an object with angles, indentations, and protrusions vs. one with only smooth, round edges and surfaces) were considered with studies focused on texture. Only studies that used objects differing configurationally (e.g., an object with angles, indentations, and protrusions vs. one with the same features but in a different spatial arrangement) were classified as studies focused on shape per se.

When the assorted studies pertaining to haptic perception during infancy were reviewed within the organizational scheme described above, a developmental sequence for the emergence of haptic sensitivity to the various object properties became apparent. This timetable is depicted in Figure 1, which serves as a summary of the literature review we conducted (for complete details, see Bushnell & Boudreau, 1991). The figure indicates, first of all, that there are many gaps in the literature on haptic perception during infancy. Most of the work conducted has focused on either texture or some sort of shape distinction, and nearly all of it has involved infants aged 6 months or older. Thus, one important consequence of our review was a call for further normative research on infants' haptic perceptual abilities.

Notwithstanding the need for further documentation, the evidence available and

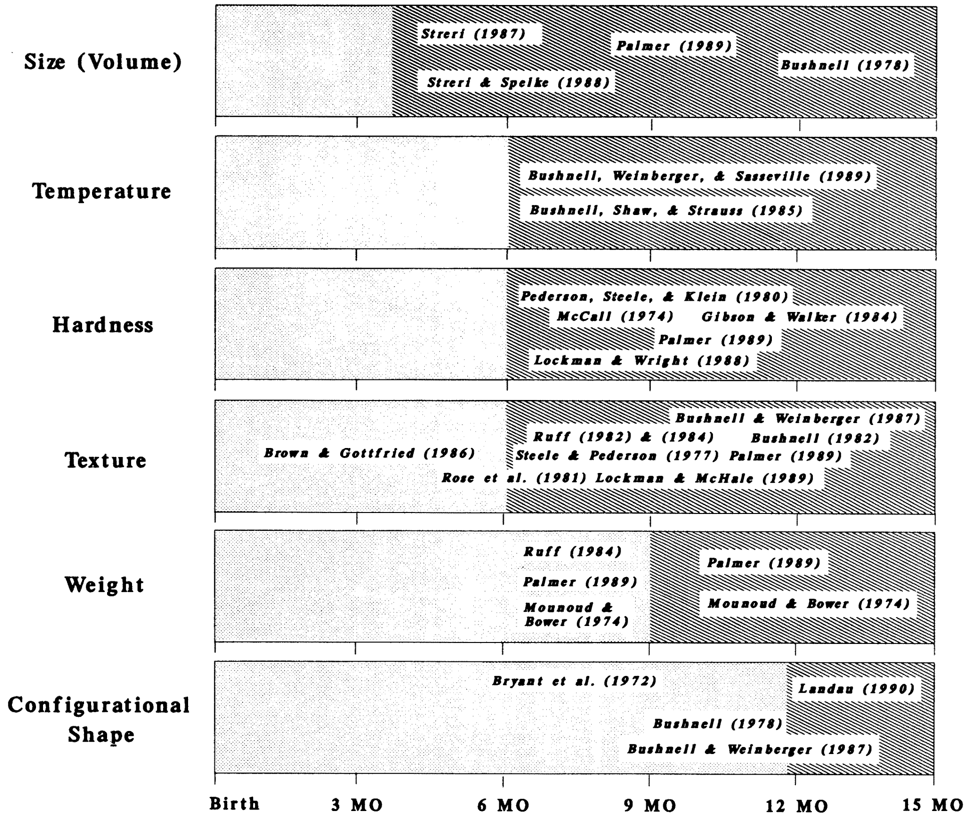

FIG. 1.—An illustration of the timetable for the development of haptic perception derived in Bushnell and Boudreau (1991). For each object property, citations are placed approximately according to the age of the infants studied. The light or left-hand portions of each timeline indicate ages that either have not yet been studied (no citations listed) or that have yielded null results. Dark or right-hand portions indicate ages for which there is positive evidence for discrimination of the object property. Citations that "straddle" both portions of a timeline refer to studies that yielded both positive and null results for infants of the indicated age.

cited in Figure 1 suggests that infants may be able to haptically perceive object size (volume) very early on, probably even during the first months of life. In the case of temperature, the only empirical evidence available involves 6-month-olds, who demonstrated the ability to perceive temperature with the hands. Although they have not been formally studied as yet, the commonplace observation that very young infants withdraw their hands from uncomfortably hot or cold stimuli suggests that they too may be capable of perceiving temperature haptically. The situation with respect to hardness is similar to that for temperature. Reliable investigations have been conducted only with infants 6 months of age and older; these indicate that by this age, infants can haptically discriminate hard objects from flexible or compressible ones. Rochat (1987) reported that younger infants may likewise be able to haptically perceive hardness; however, the dependent measures in this study could have simply reflected the grasp reflex, so whether very young infants can perceive hardness with the hands remains unclear.

For each of the other object properties with which we are concerned, the age at which haptic sensitivity emerges can be more precisely identified, as both positive and null results exist in the literature to bracket the onset time in question. As Figure 1 shows, there is ample evidence that from about 6 months on, infants can haptically perceive texture. The perception of texture per se has not been investigated with infants younger than 6 months; however, the null results from several studies employing featural shape differences, which we have construed as relevant to texture perception, suggest that infants younger than 6 months may not readily perceive texture with the hands. The object property of weight has received very little attention in the empirical literature on infant haptic perception. However, what little evidence there is includes null results for younger infants and positive findings for older ones and therefore suggests that the ability to perceive weight emerges at about 9 months of age. Similarly, the few studies investigating infants' haptic perception of configurational shape have yielded both null results and positive findings; the way these results fall with respect to age suggests that haptic sensitivity to configurational shape emerges sometime after 12 or 15 months.

Thus, although certain aspects of the timetable still must be fleshed out, there seems to be a consistent order in which haptic sensitivities to particular object properties unfold developmentally. As intimated in the introduction, we think this perceptual sequence can be explained in terms of constraints imposed by aspects of motor development. This idea stems from a consideration of recent work on adults' haptic perception. In particular, we have relied on an intriguing series of studies by Roberta Klatzky and Susan Lederman (see Klatzky, Lederman, & Metzger, 1985; Klatzky, Lederman, & Reed, 1987; Lederman & Klatzky, 1987, 1990), which has established that haptics is an impressive and distinctive perceptual system, with special expertise for encoding an object's material properties (i.e., what it is made of).

Klatzky and Lederman explain the perceptual abilities of the hands with reference to a set of stereotyped hand movements, which they call *exploratory procedures* or "EPs." They note that these hand movements maximize the sensory input corresponding to certain object properties, and in their empirical work they have documented strong linkages between certain profiles of hand movements and the apprehension of certain object properties. For example, when subjects were asked to assess an object's texture, they engaged in the "lateral motion" EP, rubbing their fingers back and forth across the surface of the object; when asked instead to assess an object's weight, they engaged in the "unsupported holding" EP, resting the object in the palm and lifting it away from the supporting surface repeatedly. By comparing performance across trials on which subjects were restricted to the use of single, prespecified EPs, Lederman and Klatzky (1987) identified the EPs that are most efficient (i.e., accurate and quick) and in some instances necessary for extracting information about specific, individual object properties. Figure 2 (adapted from Lederman & Klatzky, 1987) depicts the hand movement patterns they found to be optimal for apprehending the object properties involved in our review of infants' haptic perceptual abilities.

The implication of Klatzky and Lederman's work for perceptual development is that the limitations of infants' abilities to execute certain hand movements would restrict what they might perceive about objects from handling them. If an infant is not able or inclined to move the hands in the way most effective for apprehending a certain object property, then the infant would be unlikely to perceive that object property with any degree of precision. Thus, the onset of

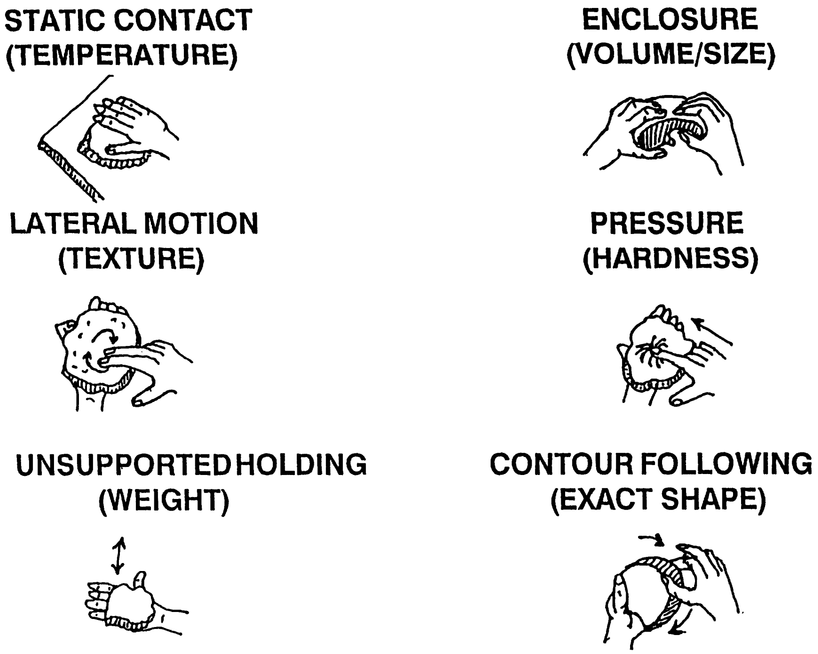

FIG. 2.—An illustration of the hand movement patterns found to be optimal for apprehending specific object properties (adapted from Lederman & Klatzky, 1987; printed with the permission of these authors and their publisher, Academic Press).

the ability to make hand movements that approximate a particular EP might determine a lower bound for when infants could exhibit sensitivity to the corresponding object property.

Pursuing this line of reasoning, we note that infants' manual behavior toward objects seems to progress through three phases during the first year of life. These phases are illustrated in Figure 3. In the first phase, from birth through about 3 months of age, infants simply clutch hand-held objects tightly in the fist; this behavior is largely controlled by the palmar grasp reflex which is present even before birth (Erhardt, 1973; Twitchell, 1965). The clutched object is typically either simply held in the one hand, brought to the mouth (Rochat, Blass, & Hoffmeyer, 1988), or brought to midline and also clutched with the second hand (White et al., 1964). If the fingers move at all, they open and close synergistically, in a "kneading" pattern.

The clutching behavior of young infants resembles the static contact and enclosure EPs identified by Lederman and Klatzky (1987). Likewise, the kneading behavior that sometimes accompanies clutching might be considered a rudimentary form of the pressure EP. Thus, following Lederman and Klatzky's work, very young infants exhibit manual behaviors that are adequate for haptically perceiving temperature, size, and perhaps hardness. In accord with this, the available evidence allows that very young infants might be able to haptically perceive precisely these three properties (see Fig. 1). Admittedly, there are positive results with infants 0–3 months old only for size perception, but at least there are no null results to undermine the possibilities that such young infants may perceive temperature and hardness, as there are for each of the other three object properties.

It is worth noting here that several researchers have reported hardness and texture perception on the part of very young infants when they experience the stimulus objects *orally* (see Gibson & Walker, 1984; Meltzoff & Borton, 1979). Although we have not included these findings in our discussion, on the grounds that oral exploration is a separate modality from manual exploration, such reports do fit nicely with the idea that motor abilities may determine perceptual ones. The movements that young infants can make with their mouths are considerably more intricate than the clutching they engage in with their hands. For example, active sucking involves cyclicly pressing the tongue against the roof of the mouth and

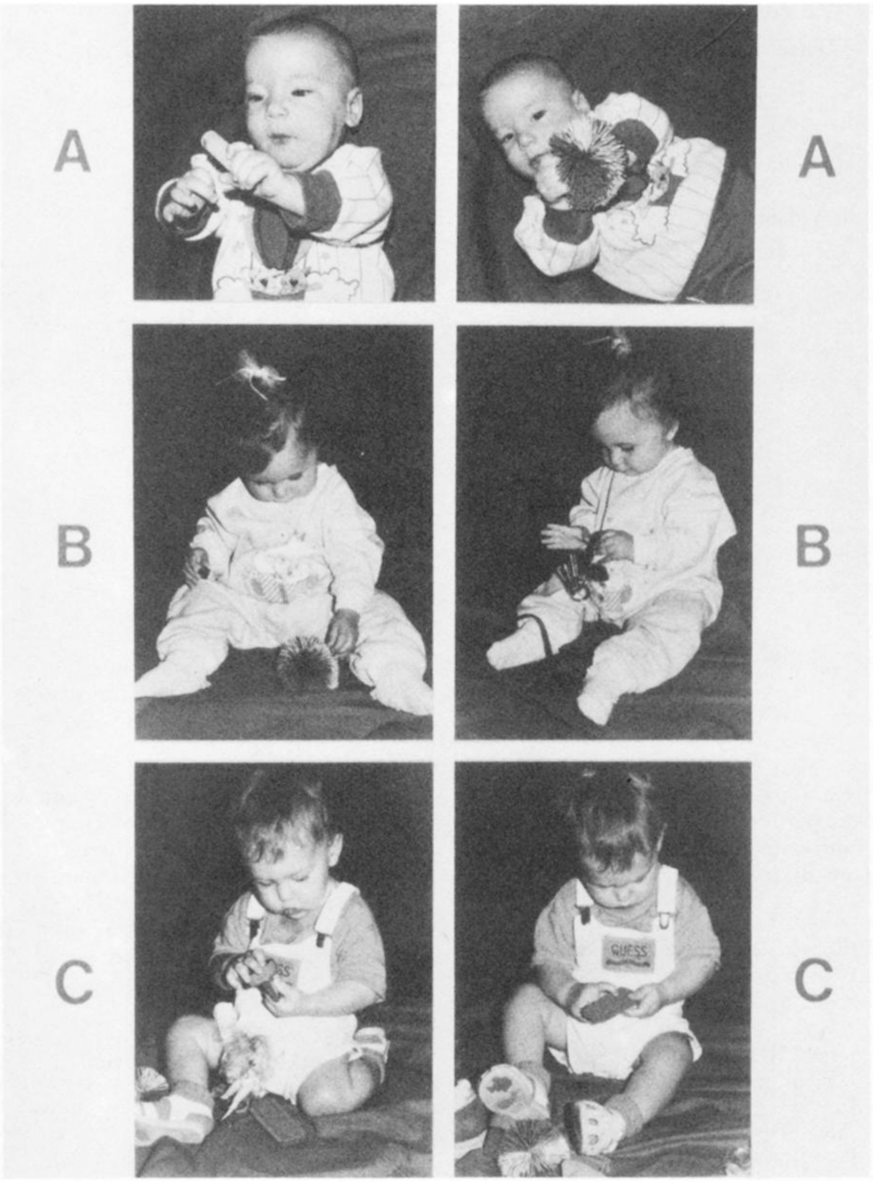

FIG. 3.—Photographs showing the three phases of infants' manual behavior toward objects: (*A*) *clutching* (birth through about 3 months of age), (*B*) *rhythmical stereotypies* (4 to about 10 months of age), and (*C*) *complementary bimanual activities* (10 months on).

drawing it backwards over the surface of the mouthed object. Such tongue movements may be considered analogous to the pressure and lateral motion EPs described for the hands, and thus they permit young infants to perceive hardness and texture orally, although these infants have yet to develop comparably complex hand movements for perceiving the same properties haptically.

At about 4 months of age, though, infants begin to move their hands under visual control and to exhibit more differentiated finger movements (Piaget, 1952; White et al., 1964). This advance in motor ability is considered to be a function of neurological development, changing biomechanical constraints, motor practice, and self-discovery. In this second phase now, infants' manual behavior with objects is characterized by repetitive finger and hand movements, called "rhythmical stereotypies" (Thelen, 1979, 1981) and, if accompanied by looking, "examining behavior" (Ruff, 1986; Uzgiris, 1967). These stereotypies peak in frequency at 6 or 7 months of age; they include scratching objects, rubbing them, waving and banging them, squeezing and poking them, and passing them from hand to hand. Such activities constitute the predominant form of play with objects until 9 or 10 months of age (Belsky & Most, 1981; Fenson, Kagan, Kearsley, & Zelazo, 1976).

The manual stereotypies infants engage in during this period are akin to certain EPs more intricate than those approximated by the clutching and kneading of the previous phase. Poking objects resembles the pressure EP even more closely than younger infants' kneading does, and scratching and rubbing objects are very similar to the lateral motion EP. Waving objects, banging them, and passing them from hand to hand all involve repeated or sustained lifting away from the support surface, and so they are like the unsupported holding EP. Thus, in the middle of their first year, infants exhibit manual behaviors similar to those identified as efficient for perceiving object hardness, texture, and weight. Congruently, it has been observed that haptic sensitivity to hardness is clearly evident by 6 or 7 months, if it is not present before then, while haptic sensitivity to texture emerges at about 6 months and seems to be absent at younger ages (see Fig. 1). The literature also indicates that haptic sensitivity to weight commences sometime after about 9 months of age, rather later than infants' waving and so on might lead us to predict, but, in any event, not before infants manifest such motor behaviors.

The repetitive hand movements of the second phase are ordinarily carried out with just one hand, while the other hand stabilizes the object against a surface or helps to maintain the infant's tenuous sitting posture (see Fig. 3*b*). By 9 or 10 months of age, however, infants have developed the torso strength and postural control necessary for independent sitting (Rochat & Senders, 1990). Now the second hand can be employed in object manipulation along with the first, and infants enter the third phase of manual behavior toward objects. During this phase, infants engage in "complementary bimanual activities" (Bruner, 1970; Ramsey, Campos, & Fenson, 1979; Ramsey & Weber, 1986); they typically use one hand to position or operate one part of an object while they manipulate another part of the same object with the other hand (see Fig. 3*c*). In addition to both hands being engaged, the hand and finger movements are less repetitive than in the previous phase and more tailored to the particular object being manipulated at the moment (Belsky & Most, 1981; Fenson et al., 1976).

Bimanual activity such as infants begin to exhibit at about 1 year of age is involved in the contour-following EP described by Lederman and Klatzky (1987). In the execution of this EP, one hand holds and maneuvers the object while the fingertips of the other hand are moved smoothly and nonrepetitively over its edges. Of the various EPs Lederman and Klatzky studied, contour following was the only one that proved useful for perceiving configurational shape. Thus, toward the end of their first year (and not before then), infants become able to make the sort of complex hand movements that are apparently necessary for perceiving configurational shape. The results summarized in Figure 1 conform with this; haptic sensitivity to configurational shape seems to emerge later than sensitivity to the other object properties considered, at some time after the first 12 or 15 months of life.

The preceding elaborations of each developmental phase of manual behavior are consistent with the idea that motor development may determine the sequence in which haptic perceptual abilities unfold. Within each phase, the kind of hand movements infants can execute circumscribes the object properties to which they show haptic sensitivity. That is, where infants of a given age are able to execute the hand movements corresponding to a particular object property, the empirical literature indicates that they may be able to discriminate objects differing with respect to that property. The only established exception here involves sensitivity to the property of weight, the emergence of which seems to come well after that of the related manual behavior. This "lag" will be addressed later. Of greater importance to the argument, it holds *without* exception that if an object property corresponds to hand movements more intricate than infants of a given age can execute, then objects differing with respect to that property are not discriminated by infants at that age. As we indicated at the outset, the developmental inability to execute appropriate hand movements may serve as a constraint or as a "developmental brake" on the ability to perceive a certain object property.

The argument that the timetable for haptic perception is mainly determined by motor development is all the more plausible because other candidate explanations for the sequence do not fare as well. Infants are not exposed earlier or more frequently to haptic variations in object size and temperature than to variations in object texture, weight, and configurational shape, for instance. Nor is it the case that the earlier perceived properties are more meaningful than the later perceived ones for adaptive behavior, object identification, or any such infantile purpose. Neither do the later perceived properties incorporate the earlier perceived ones as components, in the "cumulative complexity" sense that some later-acquired grammatical morphemes incorporate earlier-acquired ones (Brown, 1973). It is true that the haptic perception of configurational shape may require a mnemonic ability to integrate across time that is not necessary to the perception of temperature or size, for instance. However, it seems unlikely that this accounts for the late emergence of configurational shape perception, because infants much younger than 12 months evidence abilities to integrate across time in the context of perceiving rhythm, melody, and motion. In sum, the high degree of "fit" between motor development regarding the hands and perceptual development regarding the same, together with the lack of any other compelling explanation, makes a convincing case for the determining role of motor development we want to emphasize.

Example 2: The Development of Visual Depth Perception

To broaden the argument made with the example of haptic perception, we will outline a second instance in which motor development may determine aspects of perceptual development. This second example concerns the development of depth perception, that is, the ability to perceive the three-dimensional layout of objects and surfaces in the environment. In contrast to the case with haptic perception, the origin and development of depth perception has been a long-standing topic of interest; speculations and arguments about this issue were prevalent in the philosophical writings of the seventeenth century that gave rise to the discipline of psychology. The explosion of research on infancy in the last 3 decades includes numerous investigations of infants' abilities to perceive depth.

In our discussion, we will rely on an organization of the literature on depth perception during infancy provided by Yonas and his colleagues. This scheme is detailed in several review chapters (e.g., Yonas, Arterberry, & Granrud, 1987; Yonas & Granrud, 1985a, 1985b; Yonas & Pick, 1975); hence, we will merely summarize its essentials here. As Yonas notes, there are numerous "cues" to depth or sources of visual information regarding spatial layout. These are frequently grouped into three classes: information conveying depth may be kinetic, binocular, or static monocular (pictorial). In a program of research spanning the last 15 years, Yonas's strategy has been to isolate individual cues to depth within each class and to determine at what age infants first exhibit sensitivity to each such isolated cue. This research has demanded considerable ingenuity in concocting appropriate stimulus displays and devising control conditions necessary for interpreting the results. An important outcome from the whole series of experiments is the finding that "sensitivity to the three classes of spatial information seems to develop in a sequence: Sensitivity to kinetic information appears first, then sensitivity to binocular information, and finally sensitivity to pictorial information" (Yonas & Granrud, 1985a, p. 63).

From the staggered onsets of sensitivity to the three different classes of depth information, Yonas and Granrud (1985b) infer that different underlying mechanisms may be responsible for the three types of depth perception. To explain the particular sequence observed, they focus on the emergence of constraints (inherent assumptions) that may operate in the visual system and on the development of neurophysiological substrates for depth perception. Here we raise the possibility that motor development may be a determining factor. As was so with the haptic perception of particular object properties, a focus on the stimulus information involved in each type of depth perception implicates certain motor abilities as important. Therefore, the developmental courses of the motor abilities in question may dictate when in development infants might first exhibit the corresponding sorts of depth perception.

The situation for depth perception based on kinetic information will be considered first. Kinetic cues for depth include optical expansion/contraction and motion parallax; both derive from the geometric fact that with either object or observer movement at a constant velocity, the retinal image of an object displaces with a velocity related to the object's distance from the observer. The closer an object is to an observer, the faster its image on the retina expands as the object moves steadily toward the observer or the observer toward it. Similarly, the closer an object is, the faster its image on the retina displaces laterally as the object or the observer moves with constant speed laterally. Because of these relations, simple movements of the head produce kinetic information related to the 3-D layout of an array of objects—to-and-fro movements generate optical expansion/contraction and side-to-side movements generate motion parallax.

To accurately perceive depth from patterns of retinal expansion and displacement, however, the observer must be able to distinguish retinal changes arising from self-motion from those arising from true object motion. For instance, the retinal image of a near, stationary object could expand or displace more slowly with head movement than the retinal image of a farther but actually moving object. To disambiguate the kinetic information in such a situation, the observer might hold the head still for a moment to assess the one object's actual velocity so that this could be "subtracted" from its velocity during head movement, leaving only the retinal change corresponding to distance. Such behavior requires good motor control of the head; the observer must be able to move the head and hold it still "on command," and also needs to "know" when the head is in motion and when it is not.

The above analysis suggests that motor control of the head may be integral to depth perception from kinetic information. It is known that such control is one of the earliest motor achievements during infancy. Voluntary head turns to track visual stimuli and to localize auditory stimuli are observable in certain postural contexts even during the newborn period (Brazelton, 1973; Muir & Field, 1979; Zelazo, Weiss, Randolph, Swain, & Moore, 1987), and "lateral head movements" and "head erect and steady" are age-placed at 0.1 months and 1.6 months, respectively, on the Bayley Scales of Motor Development. Head control is further refined and extended to longer and longer durations over the next several weeks, so that for the most part, the conceivable motoric limitations on depth perception from kinetic information are surmounted by 2–3 months. This is entirely consistent with the timetable for depth perception identified by Yonas; sensitivity to kinetic information, especially to optical expansion/contraction, is clearly evidenced by 3-month-olds and may be present in infants as young as 1 month of age (see Yonas, 1981; Yonas, Pettersen, & Lockman, 1979).

The second class of depth information to emerge, binocular information, derives of course from the anatomical fact that our two eyes are located in slightly different positions in space. This difference in viewpoint means that the two eyes receive somewhat different images of three-dimensional scenes. Specifically, when both eyes fixate a given object in 3-D space, the images of other objects closer or more distant than the fixated one fall on noncorresponding or disparate points on the two retinas. The nature and degree of this *disparity* corresponds to the positions in depth of the nonfixated objects relative to the fixated one. In essence, by comparing the views of the two eyes, one can perceive which of two objects is closer and how much closer it is.

The perception of depth relations from retinal disparity (stereopsis) normally requires that the two eyes fixate (foveate) the same object or place in space. Such binocular fixation provides a common retinal reference point, which permits images of nonfixated objects to be located relative to one another. There is ample empirical and clinical evidence that stereopsis is dependent on binocular fixation; indeed, the neural mechanisms involved in binocular depth perception do not even develop in cases where engaging in binocular fixation is precluded during early visual experience (Banks, Aslin, & Letsin, 1975; Movshon & Van Sluyters, 1981). Binocular fixation in turn is achieved via vergence eye movements. In these movements, unlike in saccadic or smooth pursuit eye movements, the eyes are rotated in opposite directions, bringing the two lines of sight to an intersection at the fixation point.

Thus, it seems that oculomotor control sufficient for accurate vergence movements may be integral to depth perception from binocular information. Aslin (1977) found that infants as young as 1 month of age are capable of making appropriate vergence movements; however, vergence responses were inconsistent, limited to certain viewing distances, and sluggish until 3 months of age. Furthermore, infants did not exhibit saccadic movements to reestablish disrupted convergence until 6 months of age. Aslin (1987) has speculated that precise oculomotor control may be difficult for young infants because the anatomy of the ocular system (e.g., the mass of the eyeball) changes so drastically over the first few months of life. At any rate, the imperfect oculomotor control of young infants may preclude systematic binocular fixation and therefore inhibit the development of binocular depth perception. Both Aslin (Aslin & Dumais, 1980) and Yonas and Granrud (1985a) also identify this motor limitation as a possible determinant for the age of onset for stereopsis. Yonas's work (Gordon & Yonas, 1976; Yonas, Oberg, & Norcia, 1978) and studies by several others (Birch, Shimojo, & Held, 1985; Granrud, 1986) all indicate that the ability to perceive depth from binocular information is present by 4–5 months of age but not before.

The third class of depth cues, static monocular cues, is a motley collection of types of information available in the retinal image of a single eye. These include relative size, texture gradients, familiar size, shading, linear perspective, interposition, and others. What these "pictorial" cues have in common is that to perceive depth from any of them, additional information or assumptions are required. This additional information is *not* available in the stimulus situation of the moment; it is supplied from "top down." Thus, to perceive depth from relative size and texture gradients, one assumes that the differently sized images represent items that are approximately equal in real size. To perceive depth from familiar size, one utilizes prior knowledge of the object's real size in conjunction with its current retinal image size. To perceive depth from linear perspective, one relies on the assumption that angles represented in the retinal image are actually right (90°) angles. To perceive depth from interposition, one may rely on prior knowledge of the complete form of a partially imaged object. In the case of a novel object, one assumes that its form is "good," hence forcing the perception that the partial or "nongood" image represents an object *behind* and therefore farther away than the occluding object. Violations of such top-down knowledge and assumptions are the source of many familiar perceptual "illusions."

A striking finding across Yonas's experiments investigating infants' responsiveness to individual static monocular cues is that sensitivity to each of them emerges at very much the same point in development, between 5 and 7 months of age. This synchrony in spite of the diversity of types of information involved suggests that a single overarching mechanism or constraint affects the development of sensitivity to static monocular depth information. Yonas and Granrud (1985a) note that infants younger than 5 months of age are generally insensitive to configurational information, implying that this perceptual limitation may be important. Another possibility is that young infants may not have the capacity to process current stimulation and intrinsic (top down) knowledge together, as is required for perceiving depth from pictorial information. However, young infants are not insensitive to all aspects of configuration (see, e.g., Bornstein & Krinsky, 1985; Van Giffen & Haith, 1984), and their behavior in many habituation studies indicates that they can process current stimulation in light of stored information.

Following the approach taken throughout this article, we propose that some aspect of motor development may be critical to depth perception from pictorial information. Our suggestion here is that manipulations of objects may promote the generation of the top-down knowledge and assumptions that then are brought to bear in depth perception from static monocular cues. As Ruff (1980) has pointed out, certain manual activities with objects enable the infant to produce visual stimulation that is optimal for revealing 3-D structure. For example, whereas the 3-D shape of an object may be ambiguous from any single perspective, it is uniquely and powerfully specified by continuously changing views of the object (Wallach & O'Connell, 1953). This sort of "visual flow" information may be available to infants on a sporadic basis as they are carried about or as objects in their field of view are moved. However, infants can generate such information for themselves simply by rotating an object held in the hand. Indeed, Ruff (1984) observed that infants explore objects new in 3-D shape specifically with such rotating behavior. Inspections of objects held in the hand are also conducted at a close distance, which means that the objects are unlikely to be occluded by other objects; hence, there is less ambiguity regarding their full, veridical contours than when the same objects are viewed from across the room. Likewise, the relatively constant distance from which hand-held objects are viewed would make real size relationships readily apparent.

On several counts then, the visual information related to an object's 3-D structure is especially clear and accessible when the object is viewed while held and maneuvered in the hand. Experience of this kind might thus provide infants with knowledge regarding an object's real size and shape sufficiently robust to be drawn upon (in later encounters) in perceiving depth on the basis of familiar size and interposition with familiar objects. Furthermore, experience of this kind with a variety of objects might provide infants with sufficient "data" from which to form the assumptions about objects in general which figure in depth perception from linear perspective, relative size, texture gradients, interposition with novel objects, etc. These claims are admittedly rather speculative. However, the timing of the motor achievement we have implicated is just right. As discussed above, manipulations accompanied by looking ("examining behavior") become the predominant form of play with objects at about 6 months of age; recall that sensitivity to all of the various static monocular depth cues emerges between 5 and 7 months.

By way of summarizing, we have argued that depth perception based on kinetic information emerges as early as it does because it entails good motor control of the head, and this is attained during the first 6–10 weeks after birth. Depth perception based on binocular information entails good oculomotor control, which is not approximated until about 3 months of age; hence, stereopsis emerges subsequently, at around 4 months, and after depth perception from kinetic information. Finally, depth perception based on static monocular cues involves top-down processing with knowledge and assumptions that may be most easily generated from active manipulations of objects. The motoric ability to engage in such manipulations first appears at about 4–5 months; hence, depth perception based on static monocular cues emerges after that, between 5 and 7 months, and thus later than the other depth perception abilities. As was the case with the example of haptic perception, there is a high degree of fit between the developmental timetable for depth perception sensitivities and the ages at which the related motor abilities achieve some level of refinement.

Qualifications and Conclusions

The role we have ascribed to motor development in the developments of haptic perception and depth perception is that of a prerequisite or rate-limiting factor. In other words, infants must be able to execute the specified motor abilities in order for the corresponding perceptual abilities to emerge. Furthermore, recalling the phenomenon of developmental gradualness, we would add that to the extent a specified motor ability is limited in complexity or to certain contexts, the corresponding perceptual ability will likewise be restricted. In our two examples, the motor abilities cited are important in that they *make available* certain information required for the acquisition or operation of the related perceptual abilities. This characterization means that the motor ability is not "necessary" in the logical sense for the perceptual development; if the critical information provided by the motor ability is supplied via some other means, the perceptual development can go forward without the motor ability. For example, we have argued that the ability to make certain hand movements determines haptic sensitivity to particular object properties, because they produce the sensory information related to the properties in question. Similar stimulation would also be produced, however, if the hands *were moved* (by someone else) in the appropriate patterns or if the object moved or was moved appropriately within the hands. Under these circumstances, we presume infants could discriminate different textures or configurational shapes even if they were not able to execute the relevant hand movements themselves. Indeed, the positive results of some investigations of infants' haptic abilities may have ensued for this sort of reason, because the stimulus objects were moved around in the infants' hands by the parent or the experimenters (e.g., Lockman & McHale, 1989; Rose et al., 1981). Likewise, if the visual information generated by skilled object manipulations was somehow simulated and presented to young infants not yet capable of the same, perhaps they could evidence depth perception based on familiar size or linear perspective. These conjectures suggests some interesting avenues for further research. We maintain, however, that in the normal course of events, self-produced movements are the surest and most frequent source of the information requisite to the perceptual abilities in question; it is with this understanding that motor development has been considered rate-limiting for aspects of haptic perception and depth perception.

It must also be noted that in most cases, motor development is not "sufficient" in the logical sense for perceptual development, either. That is, we do not consider motor development the *only* factor influencing the developments of haptic and depth perception; these are undoubtedly multiply determined. In some instances, the critical motor ability may be the last prerequisite piece to fall into place and therefore is genuinely *the* rate-limiting factor. In other instances, the critical motor ability may be achieved before other important conditions are met; in such cases, the emergence of the perceptual ability in question may be delayed relative to the onset of the corresponding motor ability. Haptic sensitivity to weight represents such a case. As discussed earlier, this sensitivity seems to emerge after about 9 months of age, whereas infants exhibit the requisite hand movements (waving and banging) from about 6 months. We have argued elsewhere (Bushnell & Boudreau, 1991) that sensitivity to weight may be delayed on account of cognitive considerations; while they are engaged in waving and banging, infants' attention is probably directed toward the intriguing auditory and visual consequences of such activities, and thus the stimulus variations corresponding to weight differences escape them. If attention to weight were forced, for example, by removing the auditory and visual consequences of banging and waving, then perhaps infants would exhibit sensitivity to weight at earlier ages than they do ordinarily. Along the same lines, a variety of perceptual, cognitive, and social considerations might affect whether engaging in a particular motor behavior is rewarding or not, and thereby "modulate" whether a perceptual development dependent on that motor ability would emerge immediately after the motor achievement or belatedly.

Finally, we acknowledge that the proposed role of motor development in setting the course for the developments of haptic perception and depth perception remains to be empirically documented. The usual correlational, deprivation, and enrichment approaches come to mind, along with other more experimental manipulations such as the "simulated movement" procedures mentioned above. In one or more of the phases of development we have discussed, motor abilities may prove to be less important than we have supposed. Observations such as Decarie's (1969) on the cognitive skills of thalidomide babies give us pause, for example, although we would want to consider the precise nature of their residual motor abilities. However, if our arguments provoke research designed to document or disprove them, this article will have fulfilled its purpose. Our principal intention is to bring to the fore the serious possibility that motor development may play a significant role in determining developmental sequences in other domains. By presenting the case for motor development as a determinant, we provide encouragement and justification for the current resurgence of interest in motor behavior during infancy. We also express some concern about the current tendency toward studying motor behavior and development in isolation. Although not invariably secondary to it, as traditional psychology had it, motor development does indeed interact with mental development. In short, we are in favor of keeping the infant's mind together with the body in discussions of development, but in new and more various causal configurations.

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