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Discussion

Babies' steps make giant strides toward a science of development

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Why might a paper on infants' leg movements be one of the most widely cited papers in a general journal on infancy? Thelen et al.'s article (1984) (re-published in this issue) and her related work settled a long-standing argument about the fate of a newborn reflex. The implications of this work, however, extend far beyond the scope of infant stepping. It changed the way researchers think about motor development and came to represent a new theory of general developmental processes. Most important, Thelen's strategy of using a highly specialized paradigm as a model system for understanding general developmental processes promises to pave the way for a real science of development.

Babies' first steps have always been a compelling phenomenon in developmental psychology. Perhaps because walking is such a fundamental skill for human functioning, so pervasive across individuals and cultures, so accessible to the untrained eye, and its development so seemingly transparent to our common sense intuitions, the image of an infant toddling across the floor makes an especially powerful paradigm for understanding the process of developmental change. Since the 1930s, infant walking captured the essence of a maturation theory of development. Like body growth, development of sex characteristics, changes in the neurophysiology of the brain, and other changes attributed to biological maturation, motor skills appear to unfold inexorably over time. Upright locomotion represents the culmination of the steady march of motor skills through infancy. Since the 1980s, when Thelen and her colleagues published their studies of physical growth and the newborn stepping reflex, infant walking took on a new image. Babies' steps became the paradigmatic illustration for dynamic systems theory, the most serious challenge to the maturationist perspective.

In the 1930s and 1940s, research on motor development was in its heyday. McGraw, Gesell, Shirley, and their contemporaries obtained detailed descriptions of changes in infants'

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motor skills as a means for making inferences about underlying changes in the central nervous system (Gesell, 1946; McGraw, 1945; Shirley, 1931). As McGraw (1945) put it, her studies were initiated "for the expressed purpose of determining the relationship between behavior development and the maturation of neural tissues, particularly those of the brain" (p. xi). The fascinating U-shaped trajectory of infants' stepping movements was a case in point. The traditional explanation for the appearance, disappearance, and subsequent reappearance of infants' steps proposed maturation of the central nervous system as the primary causal agent (McGraw, 1940). According to the traditional account, reflexive movements are inhibited by the maturing cortex and voluntary stepping reappears under cortical control. In the 1970s, the cortical maturation view was challenged by Zelazo and co-workers (Zelazo, 1976, 1983; Zelazo, Zelazo, & Kolb, 1972) findings that daily exercise prolonged newborn stepping movements and accelerated the onset of independent walking. Zelazo's learning hypothesis also relied on the central nervous system for driving the developmental progression in infants' stepping movements. On Zelazo's account, newborn stepping movements disappear due to disuse, and practice lifting the legs converts the reflexive behavior into an instrumental response under cortical control.

Thelen and colleagues offered a more parsimonious explanation. On their account, stepping movements disappear because infants' legs become too heavy to lift in an upright position. Stepping movements reappear when infants' leg muscles become strong enough to hoist the limbs against gravity. As evidence for their biomechanical account, Thelen showed that infants display the same pattern of alternating leg movements while lying on their backs as they do while standing upright (Thelen & Fisher, 1982), and supine kicking movements never disappear during infants' first year (Thelen, 1981). Slimmer babies produce more steps than chubbier ones and higher levels of arousal are correlated with increased frequency of stepping (Thelen, Fisher, Ridley-Johnson, & Griffin, 1982). Infants can continue to produce upright stepping movements throughout their first year if a motorized treadmill augments leg strength by stretching the leg backward and allowing it to pop forward like a spring (Thelen, 1986). Most troubling for the maturation and learning accounts was Thelen's (1984) (re-published in this issue) experimental manipulation of infants' leg mass and muscle strength. Babies who normally took steps stopped stepping when their legs were weighted to simulate the leg fat gained over their first 2 months. Babies who normally had stopped taking steps stepped once again when their legs were submerged in a tank of water to alleviate the effects of gravity. Cortical maturation and learning were beside the point.

Thelen et al.'s demonstration that homely peripheral factors such as leg fat, muscle strength, gravity, and inertia can operate as causal agents had a tremendous impact on our understanding of motor development. While Thelen's group was observing changes in infants' leg movements in developmental time, researchers in adult motor control were discovering the importance of peripheral factors for controlling movements in real time. Biomechanical factors began to supplant centrally programmed motor schemes in researchers' way of thinking. The paradigm shift in adult motor control was due largely to the rediscovery of Bernstein's (1967, 1996) classic papers (now translated into English) and their recognition of Gibson's (1979) concept of affordances. Bernstein's insight was that the CNS can only play a limited role in motor control, that of initiating muscle actions. Gravity, inertia, and the visco-elastic properties of the joints—none of which are controlled by the CNS—also contribute to the total force underlying movements. For example, if you lift your arm upward from a stationary position at your side, muscle force contributes significantly to the total force required for the movement. However, if you drop your arm downward from overhead, the movement is nearly entirely controlled by passive forces. Gibson's complementary insight was that actions do not occur in a vacuum (even a vacuum filled with gravity). Rather, the properties of the environment both constrain and support the range of possible movements. For example, walking is impossible unless the floor is appropriately stable, flat, rigid, wide, and with sufficient traction to support the movements required for balance and propulsion.

Thelen showed that the same principles which operate in the real time control of movements also operate in developmental time. In particular, changes in infants' body growth and strength can affect the appearance, disappearance, and quality of movements in infants' repertoires. Thelen's work had the same impact on researchers' way of thinking about motor development as Bernstein's and Gibson's work had on researchers' thinking about adult motor control. The CNS, albeit more exciting in many scientists' view than the hip joint or the extensor muscles, has no privileged status in controlling movements on any time scale.

An historical irony is that the early pioneers in motor development also explicitly acknowledged that peripheral factors such as body dimensions, muscle strength, joint elasticity, gravity, effects of the substrate, and so on are important for the onset and offset of motor skills and differences in the way skills are performed. Gesell (1939), after all, coined the term "reciprocal interweaving" to refer to how changes in body dimensions and muscle strength might result in asynchronies in interlimb coordination and stage-like changes in skills such as crawling. McGraw's (1935) remarkable studies of infants swimming under water, climbing down slopes and pedastals, and balancing on roller skates showed that differences in the substrate are linked with differences in patterns of interlimb coordination. Both McGraw (1945) and Shirley (1931) reported differences in the timing and patterning of walking due to different rates of body growth and muscle strength. All of these contributions are prominently noted by Thelen in her papers. Why then might the early pioneers be pigeon-holed as maturation theorists despite their substantive work on peripheral factors? And why might researchers have failed to recognize the significance of peripheral factors in motor development prior to Thelen's work on infant stepping? Perhaps it was the historical context and the difference in emphases. The 1930s was so rife with debate over nature and nurture that the leading theorists conducted co-twin studies of enrichment and deprivation in an effort to separate biological maturation from environmental influence (Dennis, 1935; Gesell & Thompson, 1929; McGraw, 1935). Moreover, the early workers emphasized developmental norms and qualitative descriptions of stage-like universal progressions over individual differences, quantitative analyses, and variability in performance. In fact, the success of the early pioneers in equating motor development with maturation may have contributed to the demise of motor development as a field of study. After describing and cataloguing the ages and stages of motor skill acquisition, there seemed little left for workers to do. As a consequence, the study of motor development was practically moribund between the 1940s and the 1980s.

Thelen's elegant methods and the originality of her observations reinvigorated the field of motor development by reminding us that motor behaviors are rich, compelling, and observable. (Who else would have thought to load babies with weights or submerge them in fish tanks? Who else has the fortitude to track spontaneous kicking movements in 20 infants over 52 weeks?) More important, Thelen rekindled a general interest in motor development by making the paradigm of infant walking emblematic of her general dynamic systems theory of development. She offered readers of general developmental journals the clear and compelling case of infants' mysteriously disappearing and reappearing steps as an illustration of the difficult and abstract tenets in dynamic systems. For example, a central tenet of dynamic systems is that new developments can emerge without being hard-wired or programmed into the system (e.g., the trajectory of infant stepping can be explained without recourse to cortical maturation or learning). The confluence of many factors, each developing at its own rate, can push a system into a new behavioral configuration (e.g., walking results from concurrent changes in body growth, muscle strength, balance control, sensitivity to perceptual information, and the motivation to go somewhere, given the appropriate gravitational context and ground surface). The particular rate-limiting factor or causal agent can be non-specific or peripheral (e.g., fat legs). Underlying continuity in contributing factors (e.g., muscle strength and leg fat) can lead to stage-like discontinuities in the global configuration (stepping or not). These ideas have proven useful for understanding development in domains far afield from motor skill acquisition—language, cognition, and social interaction (Smith & Thelen, 1993).

I close with one final comment. Several notable researchers have complained that developmental psychologists seem to have given up pursuit of general principles of development (Gibson, 1994; Siegler & Munakata, 1993; Thelen & Smith, 1994). Much of the work in our journals consists of small theories about highly specialized phenomena. Dynamic systems may prove to be a general theory of development that withstands the test of time or it may not. Either way, I believe that the most important lesson from Thelen's work on infants' leg movements is that a small, clear, specialized model system, can be used to investigate large, complex, general issues. I return to my original question: Why is a paper on the specialized topic of infants' leg movements one of the most important pieces to be published in a general journal on infancy? The impact of Thelen and colleagues' beautiful studies of infants' stepping movements reverberate far beyond the coterie of investigators who conduct research on infant motor development. Thelen co-opted the image of infant walking to represent a new view of developmental change. In so doing, she provided a demonstration of how the study of a highly specialized phenomenon can serve as a model system for understanding the more general question of how development works. That may be the real progress in establishing a science of development.

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