Reflections on motor development research across the 20th century: Six empirical studies that changed the field

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Abstract

Motor development research has had a rich history over the 20th century with a wide array of scientists contributing to a broad and deep body of literature. Just like the process of development, progress within the field has been non-linear, with rapid periods of growth occurring after the publication of key research articles that changed how we conceptualized and explored motor development. These publications provided new ways to consider developmental issues and, as a result, ignited change in our theoretical and empirical approaches within the field of motor development and the broader field of developmental psychology. In this paper, we outline and discuss six pioneering studies that we consider significant in their impact and in the field's evolution, in order of publication: Halverson, 1931; Wild, 1938; Gibson & Walk, 1960; Connolly, Brown, & Bassett, 1968; Thelen & Fisher, 1982; Thelen & Ulrich, 1991. We have limited this review to empirical papers only. Together, they offer insight into what motor development research is, where it came from, why it matters, and what it has achieved.

Introduction

In a recent volume of *Advance in Child Development and Behavior*, Plumert (2018) brings together a set of papers focused on studying the "perception-action" system as a model system for understanding development. Indeed, as Thelen (1989) wrote, the developing "system" is the appropriate unit of analysis, which includes motor behavior. But such was not always the case. At the turn of the last century, motor development was studied, but as a window into the infant's mind, not as an integral part of a developing behavior "system." In the present paper, we examine how this transformation in the study of motor development occurred by highlighting six research studies that contributed to this transformation of the field from chronicling what infants and children can do, to how their action is an integral part of the developing system.

Infants roll over, sit, stand, and take their first steps in this well-known motor milestone sequence. The textbooks, reference materials, websites, and assessment batteries used across the world all include this sequence. Today, motion capture and biomechanical analyses of these actions have been added, but the sequence itself remains as first reported in the 1930s and 1940s by a collection of scientists (Ames, 1937; Bayley, 1936; Gesell, 1928; McGraw, 1932, 1940; Shirley, 1931). Most would agree that these papers and books, chronicling the infant motor milestones, were seminal works that significantly shaped the field of motor development and remain relevant today. But are there other studies that have significantly influenced our understanding of motor development and behavioral development in general?

In this paper, we describe six research studies that, we would argue, qualify as having made significant contributions to the field of motor development across the 20th century and helped shape its evolution into the present day. Although the choice of these works may be questioned by some, our goal is to initiate a dialogue about empirical research findings that have transformed the field of motor development. What we hope is that our paper will prompt others to consider additional studies that have challenged the "normal science" of their times (Kuhn,

1962). The six papers included here were selected by the authors from a group of 60 papers. Our criteria for selecting a paper included that it had sparked or signaled the emergence of a new direction for thinking and researching motor development and appeared to set the course for a new era in the history of the field. We have limited our choices to those studies published between 1928 and 1991; that is, from the start of the scientific study of motor development to the emergence of the Dynamical Systems period. Our choice to put at least 25 years between the publication of our selected studies and the present review was driven by our judgment that this was a time frame that allowed us to better evaluate a paper's significance. Previous papers on the history of motor development (Clark, 2017; Clark & Whitall, 1989) and the paper in this current volume (Whitall et al., 2018) also guided our selection of the six studies.

We have chosen to present the selected studies chronologically using a structured format. The discussion of each study begins with a full reference citation followed by a preamble, a study summary, and a discussion of its impact. In the preamble subsection, we introduce the author(s) and their study and situate the paper historically so that its break with the past and its impact going forward are clear. In the summary subsection, we briefly describe the research study. To fully understand the details of the empirical work, we encourage the reader to consult the original paper. In the impact subsection, we focus on how this work contributed to subsequent research and how it changed the field of motor development.

From naturalistic description to the scientific study of infants

Halverson, H. M. (1931). An experimental study of prehension in infants by means of systematic cinema records. *Genetic Psychology Monographs, 10(2-3),* 107-286.

Preamble: Building on Arnold Gesell's research on growth and development of motor behavior in early life, Henry Marc Halverson investigated the development of reaching and grasping (i.e., prehension) in infants aged 16-52 weeks. This pioneering work, along with Gesell's *Infancy and Human Growth* text (Gesell, 1928), marked the beginning of the

maturational period (1928 – 1946) in the field of motor development (Clark & Whitall, 1989). The maturational period saw a shift from single-subject, biographical records (e.g., Preyer, 1909a, b; Shinn, 1900) to multiple-subject, experimental studies (e.g., Gesell, 1928; McGraw, 1932). Halverson (1931) employed the newly emerging cinematographic technology to enhance his scientific method in the study of fine motor patterns.

Study summary: Halverson studied and filmed typically developing infants ages 16, 20, 24, 28, 32, 36, 40 and 52 weeks ($n \geq 12$ for each age) as they sat at a table and reached and grasped 1-inch (2.54 cm) cubes in three different conditions. In the first situation, the infants had no object in their hand; in the second and third situation, they had a cube in one hand and both hands, respectively. The resulting film was examined with frame-by-frame motion analysis of the infant's grasp actions and visual regard of the cube.

Although visual perception and reaching approaches were reported, this study's major contribution was its description of grasping development in infancy. Halverson identified ten progressive phases in grasping during the first year of life: (1) no contact, (2) contact only, (3) primitive squeeze, (4) squeeze grasp, (5) hand grasp, (6) palm grasp, (7) superior-palm grasp, (8) inferior-forefinger grasp, (9) forefinger grasp, and (10) superior-finger grasp. Younger infants (age 16-32 weeks) mainly pressed the cube against their palm for grasping, with the active involvement of thumb opposition appearing in age groups 24-32 weeks. Older infants (age 36-52 weeks) grasped the cube between the thumb and one or more fingers, which indicated that the fingers were starting to move independently from the palm. This developmental change in grasping is referred to as the transition from 'power grip' to 'precision grip.' Like many researchers during this time, Halverson discussed the development of reaching and grasping in the context of maturation.

Impact: Halverson's work signaled important changes in the field of motor development with the use of more rigorous methods (e.g., cinematography, standardized protocol) and larger

sample sizes. His detailed descriptions of grasping clearly enriched our understanding of fine motor skills. Indeed, the use of blocks or cubes appear in later infant motor development test batteries (e.g., Bayley, 1936; Frankenburg et al., 1992).

Theoretically, Halverson's results supported Gesell's principles of maturation, specifically as related to the developmental direction (Gesell, 1954). The observed trend from power to precision grips has been replicated in later research (e.g., Hohlstein, 1982; Touwen, 1976). While Halverson viewed these changes from a maturational perspective, later studies (e.g., Butterworth, Verweij, & Hopkins, 1997; Hohlstein, 1982; Newell, Scully, McDonald, & Baillargeon, 1989) revealed the effects of object size and shape on the type of grasping, indicating the influence of environmental and task constraints on the development of prehensile motor skills. Without a doubt, Halverson provided future scientists of motor development with a strong foundation for future investigations of the prehensile actions of infants in the first year of life. Indeed, in January, 2019, Google Scholar lists 434 citations to Halverson's 1931 paper which is approximately five times more than other empirical papers appearing in journals and coming out of Gesell's Lab at Yale around the same time, including papers on the ontogeny of prone behavior (Gesell & Ames, 1940, 80 citations) and reciprocal interweaving (Gesell, 1939, 104 citations).

The development of fundamental patterns of coordination

Wild, M. R. (1938). The behavior pattern of throwing and some observations concerning its course of development in children. *Research Quarterly, 9*(3), 20-24. [Based on her dissertation at the University of Wisconsin, 1937]

Preamble: Monica Wild was unique in her approach to motor development research. Unlike her contemporaries, such as Halverson (1931), Gesell (1928) and McGraw (1932), her focus was not on documenting infant motor behaviors across early development. Nor did she attempt to correlate the observed behavioral changes with neuromaturation or investigate the role of

nature and nurture. As a doctoral candidate in physical education, Wild focused her work on the complex skill of overarm throwing and set out to describe the neuromuscular changes in the "play forms of childhood" behavior (Wild, 1938, p. 20). Her objectives were (1) to study the overarm throw as a special but common type of throw, (2) to discover age characteristics, (3) to discover sex characteristics, and (4) to study the development of throwing behavior in a general way from age 2 to 12 years.

Study summary: Wild studied 32 right-handed children aged 2-12 years (with a boy and a girl at each 6-month age level for ages 2-7 years and at each year level for ages 7-12 years). The children were typically developing and had homogenous home and school environments. Wild did not justify these claims and was economical with other aspects of data collection such as what type of ball was used for throwing. Each child threw the ball as hard as possible three times, in a field that included distance scale marks, and an electric clock (intervals of 0.03 seconds). Films of each throw were analyzed in three ways: (1) to obtain the distance and velocity of the throw, (2) to translate the visual representation into verbal descriptions that were validated by percentage agreement measures, and (3) to trace body, arm, and hand positions at various stages of the throw.

Wild reported 14 independent and insightful results, but perhaps her most significant contribution was her identification of four types of throwing. Labeled simply as stages 1 to 4, she wrote: "…these types can be tentatively assigned to an age schedule and suggest a developmental sequence" (Wild, 1938, p. 22). While her data were descriptive, Wild also found high inter-correlations among key factors such as ball velocity, movement performance, timing score and acceleration of the hand with the ball. These correlations were consistent across age and sex giving Wild more confidence in the validity of her findings. Wild concluded that the identified developmental trend was towards a better mechanical means of projection (produced by timing and more segmental rotation) as well as improved balance and proprioceptive

mechanisms. Like others of her time, she speculated on the importance of maturational factors for producing the musculoskeletal changes in growth that allowed for the developing mechanics; however, she also stressed the potential influence of learning, particularly after six years of age.

Impact: The impact of Wild's work was slow in coming. The first few publications referring to her work appeared in the 1940s and 1950s (e.g., Bayley & Espenschade, 1941; Dusenberry, 1952). It was not until almost 30 years after publication that her work began to be regularly cited by motor development experts (e.g., Espenchade & Eckert, 1967; Gesell, 1972; Halverson, 1966; Wickstrom, 1970) and nearly forty years later when Roberton (1977, 1978) published her research that directly followed and expanded on Wild's work on the development of overarm throwing. Based on numerous citations between 1970 and 2000, it is clear that Wild eventually had a large influence on physical education researchers who became interested in the developmental sequences for all the fundamental motor patterns that underpin sport-specific skills. In particular, researchers at Michigan State University (e.g., Branta, Haubenstricker & Seefeldt, 1984; Ulrich et al., 1988) and the University of Wisconsin-Madison (e.g., Langendorfer & Roberton, 2002, Roberton et al., 1980) were influenced by Wild's systematic film-based approach to determining how the action of the body parts changed over time to produce a biomechanically more efficient and advanced skill form. Both the Michigan State University and University of Wisconsin researchers adopted Wild's methodological insight on studying the "hard" throw rather than an accurate or a comfortable speed throw because the action of the body segments in timing and movement will vary according to effort and purpose. Wild's work challenged us to focus on how fundamental motor skills develop beyond infancy and to do this objectively. In January 2019, there were 166 citations in Google Scholar, which compares less well to Halverson (1931), but quite well with the 154 citations for McGraw's 1940 study of the development of upright locomotion published in the *Journal of Pediatrics*.

Perhaps a better metric of the impact of Wild's work is the longevity of her contribution that continues to this day (with 21 citations since 2014 and nine citations since 2017).

Perception and action developing together

Gibson, E. J., & Walk, R. D. (1960). The "visual cliff". *Scientific American*, *202*(4), 64-71.

Preamble: Decades after Halverson (1931) and Wild (1938) described the motor behavior of infants and children, Eleanor Gibson and Richard Walk introduced the ideas that: (1) meaningful perception leads to action; (2) the environment offers or affords meaning that guides actions; and, (3) perceptual learning is a process of progressive differentiation and enrichment. In their classic study, Gibson and Walk asked a fundamental question about perception, and implicitly, action: Are our perceptions of the world innate or learned? Further, would perception be possible without the implicit knowledge of sensorimotor information from self-produced movements? Based on an earlier paradigm developed by Walk, Gibson, and Tighe (1957), the authors employed a visual cliff, which created the illusion of a drop-off on the floor displayed under a glass surface that afforded crawling. This paradigm controlled optical and tactile stimuli while protecting participants from harm with the glass surface. Gibson and Walk's experiment tested how perception (i.e., the drop-off) was coupled to an infant's' motor skill (i.e., crawling). Would infants avoid the cliff's "drop off" or crawl onto the glass surface (putting vision in conflict with touching the firm glass surface).

Study summary: Thirty-six infants ranging in age from 6 to 14 months were introduced to the visual cliff, just as they began to crawl. The researchers examined the infants' responses to the perceived downward depth using a horizontal transparent barrier that covered a checkered cloth. While the transparent barrier sat directly on the cloth on one side of the apparatus (shallow side), the cloth was dropped about four feet on the other side (deep side). The infants were placed on a center board between the two "floors" (i.e., between the shallow and deep sides). The infants' mothers alternated between standing just beyond the shallow and the deep sides of

the board, holding a bright-colored pinwheel to attract the infants to crawl to them. Of the 36 babies, 27 babies left the center board crawling on the shallow side; nine infants refused to move off the center board. Three infants crawled onto the glass of the deep side.

The authors suggested that the babies' avoidance of the visual cliff was an evolutionary adaptation resulting in caution and anxiety, but also in learning about their environment through action. In subsequent studies, a maturation-based explanation was chosen, with age (Walk, 1966) or crawling-onset age (Richards & Rader, 1981) proposed as the major predictors of avoidance behavior. More recent studies favor a learning hypothesis (e.g., Campos et al., 2000; Kretch & Adolph, 2013), demonstrating that despite rapid improvement in learning to perceive what are necessarily ever-changing affordances, learning one motor skill (crawling) does not help with the progression to another skill (walking). Infants perceive each new posture as a different problem in space defined by a unique set of parameters for maintaining balance (Adolph & Franchak, 2017). Thus, the perception of affordances and the motor development of infants are intimately related. In addition, others have argued that only the coupling of perception and action makes locomotion functional (Anderson et al., 2013).

Impact: The visual cliff experiment is one of the early, seminal, robust, and highly cited works [1,113 citations, January 2019, Google Scholar] with memorable images, a simple and elegant design, a common-sense appeal, and academic relevance (Adolph & Kretch, 2012). In their paper, Gibson and Walk demonstrate the role of the body in the development of perceptual-motor skills. Eleanor Gibson contributed to research in comparative and physiological psychology (Rodkey, 2015), and developed together with her husband, James Gibson, some of the most important theoretical work on ecological perception and learning in the 20th century. In many ways, the ecological psychology approach to perception and action led to the embodied cognition approach, which proposed a strong link between motor and cognitive development (Needham & Libertus, 2011). Children's motor development perturbs

the developing system generating and perceiving new sensorimotor *contingencies*, *thus*, setting the stage for the development of (higher order) cognitive skills (Gibson & Pick, 2000; Thelen & Smith, 1994). In the history of motor development, Gibson and Walk's research marks the juncture where we recognize that perception and action develop together. That is, motor development is not just the development of "motor" systems.

Processes underlying motor skill development

Connolly, K., Brown, K., & Bassett, E. (1968). Developmental changes in some components of a motor skill. *British Journal of Psychology*, *59*(3), 305-314.

Preamble: In 1968, when Kevin Connolly, Kathleen Brown and Eryl Bassett published their paper describing young children tapping between two circles, other researchers in motor development were describing when and how school-aged children were throwing, jumping, and performing a variety of gross motor skills (cf. L. Halverson, 1966; Hellebrandt et al., 1961). Espenschade and Eckert (1967) had just published the first book dedicated to motor development across the lifespan, which represented well the descriptive and normative research of the times. Perceptual-motor development was coming into view, though with the exception of Eleanor Gibson's work discussed in the last section, most research related to demonstrating perceptual-motor behaviors that children with developmental delays exhibited (e.g., Ayres, 1965; Roach & Kephart, 1966). Nevertheless, with their paper, Connolly, Brown, and Bassett provide arguably the first empirical study to focus on the underlying "processes" for the age-related changes that others were documenting.

Study summary: This study was selected because it signaled a change in motor development research from a description of what children do to an "experiment" that might reveal the process(es) underlying their action. Children of different ages performed the same task over repeated trials. The study consisted of 60 children (boys and girls) across three age groups (6, 8, and 10 years) performing 12 trials of a reciprocal tapping task. The authors wrote that they

were inspired by the work of Welford and others (Welford, 1960; Welford & Birren, 1965) who were studying the components of sensory-motor performance in adults. Connolly and colleagues questioned what changed developmentally in these components of children's motor performance. Specifically, the authors analyzed the speed and accuracy of children as they performed a 5-second bout of tapping between two one-inch circles that were 5 inches apart. It was not surprising that they found older children were faster than their younger counterparts. Interestingly, however, the 8- and 10-year-olds improved across the 12 trials while the 6-year-olds did not. This led the authors to comment that it seemed the younger children performed the task as two discrete actions - one on targeting the center of the circle and one on transporting the hand between the two circles. The scatter of their dots in the circle tended to be around the center. In contrast, the older children tapped back and forth in a smooth unitary action and their dot scatter followed along the line of the tapping action (from side to side).

Impact: Connolly, Brown and Bassett go beyond the description of improving motor performance to suggest that the results were due to the development of the perceptual and motor systems and "more important, in central information processing systems" (p. 312). That is as far as the authors would go in their discussion to which they note that "much remains to be discovered about the processes involved in the development of these important skills" (p. 313). Up to this time, our *explanations* of motor development focused on growth and/or maturation. Age differences in speeded responses (reaction time or tapping) had been documented from 1892 (Bryan, 1892) and throughout the first half of the century (cf. Bellis, 1933; Goodenough, 1935; Jones, 1937). However, these studies were just as descriptive as those examining gross and perceptual-motor skills. With Connolly and colleagues' study, we see researchers trying to understand these developmental changes in a new way. They might well be the first to use this new approach to studying motor development. With a few notable exceptions (Kerr, 1975; McCracken, 1983; Salmoni & McIllwain, 1979), the reciprocal tapping task was not an

experimental paradigm that was often employed with children. Interestingly, the authors never connected their research with Fitts' earlier work on tapping (Fitts, 1954). While the study is not highly cited [58, January 2019, Google Scholar], it has become a reference work for those who would adopt an information process-oriented approach to motor development over the next two decades (e.g., Ashton, 1976; Clark, 1982; Hay, 1981; Sugden, 1980; Whiting & Cockerill, 1972). It should be noted that, two years following the publication of this study, Connolly (1970) edited a book entitled *Mechanisms of Motor Skill Development*, that included a well-articulated set of essays by himself and other authors (e.g., Bruner, 1970) on the process-oriented approach to motor skill development, which became the more frequently cited reference (208, January, 2019, Google Scholar).

Neuromaturation is not THE explanation

Thelen, E., & Fisher, D. M. (1982). Newborn stepping: An explanation for a "disappearing" reflex. *Developmental Psychology*, *18*(5), 760-775.

Preamble: When Esther Thelen received her bachelor degree in Zoology from the University of Wisconsin in 1964, neither she nor anyone else would have predicted that she would one day change the study of infant motor development. By the 1970s, research on infant motor development had languished, in no small part because researchers in the 1920s to 1940s (e.g., Gesell, 1928; McGraw, 1940), offered a simple explanation for what drove developmental change in infancy: *neuromaturation*. Further, many in the developmental psychology field had adopted a perspective that placed a premium on the role of cognitive operations to learn and control motor skills (Piek, 2005). To these scientists, infant motor development did not represent a particularly fruitful area of study. By contrast, Thelen, trained as an ethologist, saw infancy as a rich area for studying naturalistic behaviors with an eye towards developmental adaptations. In her early work in the late 1970s, Thelen focused on infant 'rhythmic stereotypies,' nonspecific motor responses such as leg kicking or arm waving, to a wide variety

of eliciting stimuli (Thelen, 1979, 1981a, 1981b; Thelen, Bradshaw, & Ward, 1981). However, it was the 1982 work by Thelen and colleague Donna M. Fisher on the rhythmical stepping of infants that would challenge the neuromaturational approach to infant motor development.

Study summary: Using frame-by-frame video analysis coupled with electromyography from four muscle groups in the legs, Thelen and Fisher observed kicking and stepping behavior in eight typically developing infants aged 5-14 days. Were the newborns' kicks and steps separate movements or were they, in fact, isomorphic? The paradox was that throughout infancy, while newborn kicking increased in frequency, newborn stepping disappeared. If the step reflex disappearance was driven by neuromaturation of the cerebral cortex, which inhibited the reflex (Peiper, 1963), why would kicking have a different trajectory? Thelen and Fisher had an answer that would challenge the central tenet of the prevailing neuromaturational explanation. The differences, argued Thelen and Fisher, could be explained by the action's context; that is, the effects of gravity on muscle function differed when the infants were placed in different postures. As the mass of the legs increased in the developing infant, the dynamics of the moving limbs were altered. The authors argued that the strength of the muscle contractions (i.e., the rate of the firing of the motor units and/or the number of motor units recruited) might be sufficient to cause frequent and vigorous kicks when the body weight is supported in the supine position and the movement is aided by gravity. However, the infant's muscle strength may be inadequate to lift the legs or support the leg weight when the infant is upright. In other words, infants lacked the strength to lift their legs during stepping; hence, the reflex 'disappears.' In a subsequent experiment, the authors empirically confirmed their hypothesis by weighting and unweighting (in water) the infants' legs (Thelen, Fisher, & Ridley-Johnson, 1984).

Impact: Thelen and Fisher's study represents a turning point in the study of motor development not only in infancy but also across the lifespan. Thelen and Fisher, like others before, used biomechanical methods to observe the infant's motor behavior, but here they

studied the infants in a naturalistic setting to compare two supposedly different actions, stepping and kicking. Their conclusion was that newborn stepping and kicking were manifestations of the same movement. They then provided a well-argued rationale for why one behavior would disappear and one would not, based on biomechanical properties of muscles interacting with changing infant morphology and differing environmental contexts. In that same year, Kugler, Kelso, and Turvey (1982) had published their seminal conceptualization of a non-linear dynamic systems approach to motor behavior and Thelen and Fisher's work provided an empirical example of this newly emerging paradigm for motor development. The impact of Thelen and Fisher's study cannot be understated. While the publication itself was cited 358 times [January, 2019, Google Scholar], a 'ripple effect' occurred: Of the citing articles, 51 have 100 or more citations, 27 have 200 or more citations and 10 have 500 or more citations. These cascading citations reflect the beginning of a conceptual framework launched by Thelen & Fisher's study that would reinvigorate the study of infant motor development as well as motor development across the lifespan. Research citations related to motor development more than tripled in the next decade (1991-2000; Clark, 2017). To Thelen and her colleagues, developing motor skills resulted from the changing constraints of the organism, the environment, and the task at hand. Developmental change was not driven solely by the maturing central nervous system, but by the processes of a dynamic, self-organizing system.

Self-organizing, constrained developing systems

Thelen, E. & Ulrich, B.D. (1991). Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development*, *56*, 1-103.

Preamble: Less than a decade after her seminal paper on the disappearing reflex (Thelen & Fisher, 1982), Esther Thelen again challenged our views of motor development – this time on the development of walking. Much like the clever experiment that revealed a "disappearing"

reflex, Thelen and colleague Beverly D. Ulrich discovered in this work the "hidden" skills of walking by supporting pre-locomotor infants on a motorized treadmill. Again, using the sophisticated biomechanical techniques employed more often with older children and athletes, Thelen and Ulrich described the spatial-temporal interlimb coordinative patterns that emerge as the infants were repeatedly exposed to the treadmill. Their experiments appeared in the Monograph of the Society for Research in Child Development, thus providing the authors the opportunity for additional space to reinforce and expand on the conceptualizations that guided their experiments; namely, the dynamic systems approach. While the maturational perspective had faded in mainstream developmental science, it still maintained a hold on explanations of locomotor development (Forssberg, 1985).

Study summary: In what Thelen called a "dense longitudinal" study, 9 infants were studied twice each month from the age of 1 month to 7 months. Several infants continued to be tested through month 10. The motor items from the Bayley Scales of Infant Development (Bayley, 1969) were administrated every month and anthropometric measures were taken. Thelen and Ulrich employed an elaborate state-of-the-art motion capture system to measure 3-D coordinates of the two feet. Following data collection, in addition to the motion capture data, videotapes of the infants' actions were coded for leg posture and orientation. Guided by dynamic system strategies, Thelen and Ulrich found that the treadmill elicited alternating walking steps well before independent walking. With increasing age and experience on the treadmill, infants' stepping became consistent and stable (i.e., resistant to perturbation). In stark contrast to the typical age-group reports found in other studies, the authors reported their results for individuals – showing their different developmental trajectories rather than collapsing them into average scores. Individual differences were plentiful, but the authors challenged us to focus on finding the underlying dynamic processes that supported the observed individual developmental changes rather than on mean differences.

Impact: Clearly, the impact of this study on those investigating the development of motor skills and locomotion was significant. For those studying locomotion, the dynamic systems approach significantly changed how its development was studied and conceptualized (e.g., Adoph et al., 1993; Clark & Phillips, 1993; Whitall & Getchell, 1995). But it was not just locomotor development, but motor development more broadly as well as other areas of motor behavior (cf., Ulrich & Reeve, 2005). Its impact on the larger field of development was important as well. Except for Gibson and Walk's visual cliff study (1960), Thelen and Ulrich's monograph is the next most highly-cited paper of our six selected studies in motor development [802; January, 2019, Google Scholar]. While their empirical findings on the development of locomotion were important, the monograph's larger impact came from their detailed explication of the dynamic systems theoretical framework with its implications for understanding developing system.

Summary

The first half of the 20th century saw a change in the methodological approach to investigating motor development (e.g., filming, protocol design), which led to a detailed description of both infant and children's motor development. The second half of the 20th century saw a deeper and wider exploration of mechanisms driving motor development, which challenged the dominant maturational perspective and led to further development of theory concerning how motor behavior developed over time.

How these six empirical studies have had an impact on the field of motor development vary. Chronologically, Halverson (1931) and Wild (1938) introduced objective empiricism to a field that relied on more qualitative descriptive methods. Gibson and Walk (1960), Connolly et al. (1968), and Thelen and Fisher (1982), each provided major shifts in the theoretical underpinnings of our research, providing fresh explanations for developmental changes and driving new experimental approaches to answer developmental questions. Finally, Thelen and

Ulrich (1991) consolidated the dynamical systems approach to motor development and helped spawn the application of this approach to a range of disciplines that includes developmental psychology, kinesiology, cognitive development, sports medicine, robotics, neuroscience, and developmental disorders. Interestingly, the 10 authors cited came from varied scholarly backgrounds, including psychology (6), ethology (1), physical education (1), mathematics (1), and kinesiology (1). And yet all were focused on understanding the development of human motor behavior. No doubt, influential papers of the 21st century in the field of motor development will continue to represent authors from a wide range of academic backgrounds as we are challenged to answer questions that demand interdisciplinary approaches.

As we stated in the introduction, we hope that our choice of papers will spark both an appreciation of the importance of these authors' research questions, methodologies and conceptual underpinnings as well as a discussion about their subsequent impact on the evolution of motor development research. As can be seen from the representation of numbers of citations, we did not merely choose papers that are highly cited but considered those which we thought led to a change in how we conduct and think about research in the field. We also hope this paper has sparked an interest in reading the original papers. In addition, we hope this paper has created an interest in what other empirical findings influenced the "development" of motor development.

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