Motor development research: I. The lessons of history revisited (the 18th to the 20th century)

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This is the accepted manuscript version of the study cited as:

Whitall, J., Schott, N., Robinson, L. E., Bardid, F., & Clark, J. E. (2020). Motor development research: I. The lessons of history revisited (the 18th to the 20th century). *Journal of Motor Learning and Development*, *8*(2), 345-362. https://doi.org/10.1123/jmld.2019-0025

Abstract

In 1989, Clark and Whitall asked the question "What is motor development". They were referring to the study of motor development as an academic research enterprise and answered their question primarily by describing four relatively distinct time periods characterized by changes in focus, theories or concepts and methodology. Their last period was named the process-oriented period (1970-1989). In hindsight, it seems clear that their last period could be divided into two separate historical time periods: the information-processing period (1970-1982) and the dynamical systems period (1982-2000). In the present paper, we briefly revisit the first three periods defined by Clark and Whitall, and expand and elaborate on the two periods from 1970 to the turn of the century. Each period is delineated by key papers and the major changes in focus, theories or concepts and methodology. Major findings about motor development are also described from some papers as a means of showing the progression of knowledge.

Keywords: motor development, history, information processing, dynamical systems

Vibrant areas of scientific study progress, stabilize, retreat sometimes, and evolve again, ultimately answering more complex and significant questions. Indeed, the scientific study of motor development has followed such a trajectory. As a field, motor development has changed significantly from the descriptive, naturalistic studies of infants in the late 18th to early 20th century (e.g., Tiedemann, 1787; Preyer, 1881-1882/1909a-1909b). In the 21st century, scientists ask some of the same questions as those early pioneers, but they now have an array of new tools and a century of findings upon which to build their theories and hypotheses, conduct their experiments, and interpret their findings.

We will "revisit" the history of motor development research to explore how the field has evolved since Clark and Whitall (1989) wrote their paper, "What is motor development? The lessons of history." Clark and Whitall characterized the field as occurring in four distinct periods reflected by changes in focus, theories or concepts and methodology: (1) the precursor period (1787-1928); (2) the maturational period (1928-1947); (3) the normative/descriptive period (1947-1970); and, (4) the process-oriented period (1970-1989). As we revisit their paper, we bring our 21st century perspective to a two-part paper: (1) the first, to briefly re-examine and extend the original four historical periods proposed by Clark and Whitall; and, (2) secondly, to examine the field in the 21st century and propose three new approaches that occupy the same (rather than sequential) historical period. Our discussion grew out of the first meeting of the International Motor Development Research Consortium (I-MDRC) that took place in Le Boulard, France (2015) and is informed by three recent papers that reviewed the last 50 years of motor development research as part of the 50th anniversary celebration of the North American Society for the Psychology of Sport and Physical Activity (NASPSPA) (Anderson, 2018; Clark, 2017; Robinson, 2018).

Owing to its length and change of historical approach, the paper has been divided into two parts. We set the scene for Part One with a brief summary of the first three historical periods from Clark and Whitall's paper (1989). We then revise the original fourth period (the process-oriented period) into two separate, but largely, sequential periods: (1) the Information Processing period (1970-1982); and (2) the Dynamical Systems period (1982-2000). We describe these two periods in some detail and highlight papers that shaped our decision to revise the characterization of this time in our history.

Precursor Period (1787-1928)

While not specifically self-described as motor development research, the Precursor period provided great value to our study of motor development. Using the naturalistic method common at that time, the so called "baby biographers" provided detailed longitudinal observations and descriptions of infant motor behavior (Preyer, 1881-1882/1909a-1909b; Shinn, 1900; Tiedemann, 1787 as cited in Borstelmann, 1983). They were not interested in motor development, as such, but in what the developing motor capabilities could tell them about the infant's mind. Their emphasis was on the product of motor development; namely, what could babies do. During this same time period, Darwin and others were also carrying out naturalistic animal studies and writing about the role of the environment and the animals' adaptations to their surroundings. The scientific legacy of this period was longitudinal, detailed descriptive observation of babies and infants.

Maturational Period (1928-1946)

The maturational period was dominated by the central premise that the observed sequences of behavior were universal and largely inherent in the developing infant and child. The dominant scientific method was longitudinal observation and description, but now rather than studying one infant or child, studies included multiple participants. Two of the leading scientists at the time, Gesell (Gesell, 1928; Gesell & Thompson, 1929) and McGraw (1935), both conducted experiments on twins (i.e., Gesell's T and C and McGraw's Jimmy and Johnny) in order to test the relative influence of nature (neuromaturation) and nurture (environment). Although it should be noted that McGraw, in particular, emphasized the importance of experience in addition to neuromaturation. Together, their work was the beginning of an experimental approach to studying motor development. It also was the first time that the scientific goal was to go beyond the descriptions of change to understanding the broad cause(s) or process(es) of development. A major legacy of this period was the description of developmental sequences of fundamental motor skills in infancy such as reaching (see Halverson, 1931 described in Clark et al. this volume) and locomotion (McGraw, 1940).

Normative/Descriptive Period (1946-1970)

The Normative/Descriptive period emerges as the focus of the field moves from infancy to childhood. The dominant theoretical approach initially remained maturational, but over time, there was greater recognition of environmental factors and the role of learning. Compared to the previous period, the emphasis was now on the description of motor performance ─ primarily in school-aged children ─ and the methodology employed was typically cross-sectional. This emphasis was presaged in the previous period by Wild (1938), whose work is described in Clark et al. *(*this volume*)*. Developmental sequences of gross motor skills (e.g., throwing, jumping) were described in the same way they had been done for infant's motor development (e.g., Halverson, 1966; Hellebrandt et al., 1961). Added to the descriptions of the movements themselves (the process of moving) were the age-related changes in the motor outcome or the product of the movement (e.g., distance thrown or jumped). At this time, there was increasing interest in the physiological changes that occurred in children as they grew and developed, particularly as it related to physical fitness (and to puberty). This latter research measured characteristics such as children's strength, speed, and endurance (cf. Clarke & Wickens, 1962) and how these measures related to motor performance (e.g., Clarke & Degutis, 1964; Clarke & Glines, 1962; Espenschade, 1963). Researchers also became interested in understanding the effect of learning, and this was seen in the appearance of intervention studies (e.g., Smith, 1956). As this period waned, there was a recognition of the perceptual processes that are implicit in the production of motor skills (e.g., Singer, 1968; Witte, 1962). One legacy of this period was the qualitative biomechanical description of developing sports-related skills; another was the quantitative measurement of the outcomes of these skills that provided normative data of motor performance.

Process-oriented period (1970-1982)

The last period in the history of motor development proposed by Clark and Whitall was the process-oriented period that began in 1970 and continued to the time the paper was published in 1989. The authors characterized this period as one where research focused on the "processes" underlying motor development. However, in 1989, Clark and Whitall observed that there were actually two distinct theoretical approaches to motor development during this period: the information processing perspective and the dynamical systems perspective. From the vantage point afforded by the last thirty years, we propose now that the process-oriented period was actually two distinct and relatively sequential periods: the first, the Information Processing period (1970-1982) followed closely by the Dynamical Systems period (1982-2000). Although we should note that while we have demarked these as two distinct periods, science is not so easily bifurcated and research from each tradition clearly co-existed.

Information Processing period (1970-1982)

The Information Processing period was a period of exploding interest in motor development, not only in physical education/kinesiology but also in developmental psychology. The renewed interest focused on the development of processes underlying motor behaviors. This is best captured by the title of the book, *Mechanisms of Motor Skill Development,* by Connolly (1970), which Clark and Whitall (1989) identified as marking the beginning of their process-oriented period. Parenthetically, an earlier empirical paper by Connolly (Connolly, Brown, & Bassett, 1968) is arguably the first example of an information processing approach to motor development (Clark et al., this volume). The information processing approach was not a developmental theory per se, but rather a theoretical perspective or framework based on the computer as a model of the brain. The environment and the movement experience provided the sensory "input" to the computer which processed the incoming information (e.g., perceiving, selecting, and programming) and, subsequently, sent an output to the body resulting in behavior (that is, in a movement). Theoretically, the decision-making process occurred in three stages (stimulus identification, response selection, and response programming).

Researchers sought to explain developmental changes in infant and children's movement skills through hypothetical processes in the model (e.g., changing perceptual capabilities, increasing memory, etc.). A typical dependent measure was time (i.e., reaction time) representing the effect of various experimental manipulations on how long it took the children to "process" the information or "prepare" to move. Since computers consisted of "programs," that were regulated by other hierarchical programs, it was not surprising that motor behavior researchers would see motor sequences as resulting from "motor programs" (i.e., Schmidt, 1975; Keele & Summers,

1976) and that these programs were regulated by “recall and recognition schemas” (Schmidt, 1975).

For those studying motor development in young children, the combination of influences from developmental psychology and motor control/learning was enough to encourage many researchers of that era to ask how these underlying processes might themselves change over time and how this might affect movement control and coordination at different ages. For example, Connolly (Connolly, 1973) designed experiments that suggested that changes in hand skillfulness resulted from children’s increasing ability to integrate small movement sub-routines (i.e., as part of a motor program) into larger routines. Other experimenters studied age-related changes in perceptual processes (Ridenour, 1974; Williams & DeOreo, 1980), factors affecting decision-making, such as response selection and programming processes (Fairweather & Hutt, 1978; Hay, 1979), memory (Thomas, 1980) or schema formation (Kelso & Norman, 1978). Still, others addressed what are typically motor learning mechanisms such as the ability to process feedback across ages (e.g., Newell & Kennedy, 1978; Thomas, Mitchell, & Solomon, 1979). In this period, researchers studied how children’s perceptual-cognitive processes, that were assumed to control movement, changed as a function of age during childhood.

Methodologically the experiments using the information processing paradigm to investigate motor development differed from previous experimental designs in two major ways. First, while the use of cross-sectional designs remained, age was no longer *the* main independent variable. Researchers noted that simply describing differences across age did not allow for inferences about how motor skills developed. What was needed was a better understanding of how the underlying processes might change developmentally and, thus, subsequently modify the child’s motor behavior. Therefore, true experimental designs emerged.

For example, in an experiment on response selection, Clark (1982) chose to examine not only three age groups, but also the effect of two different stimulus-response conditions (compatible and incompatible) on the age groups' reaction times. The corresponding reaction time indicated how long it took each age group to select and plan the movement given the stimulus-response pairings (one easy - compatible and one hard - incompatible). If the statistical result had focused only on the main effects of age and condition, all the experimenter would have learned was that adults were faster than older children (10-year-olds) who were faster than younger children (6-year-olds) at selecting and planning their movements, and that one condition (compatible) was significantly faster than the other (incompatible). Such results are descriptive of the age-related changes that occurred, but they do not enlighten us as to the underlying processes that drive these differences.

For Clark, it was not the "main effects" that were of interest, but the *interaction* of independent variables: age and stimulus-response compatibility. Indeed, the effect of age and compatibility resulted in a significant interaction. Clark found that stimulus-response compatibility had an *age-related differential* effect on the children. Incompatible relationships were challenging for all ages (slowing down their reaction time), but for the youngest, it was even harder (raising their reaction time much more than for the older children and adults). Response selection in young children was not just slower but, in some way, different than it was in older children and adults. Researchers of this era tended to manipulate experimental variables in an attempt to detect age-related interactions that would be more revealing than simple descriptions of changing behaviors.

The second modification in experimental design from the previous era related to the motor behavior under investigation. Earlier studies examined complex and often gross motor skills, but researchers during this era focused on simple, easily controlled movements such as lifting a finger for reaction time experiments or moving a lever to a 'remembered' arm position in experiments on body positional memory (Winther & Thomas, 1981). Since the emphasis was now on how the brain controlled movement and not on the movement itself, the use of complex gross motor skills was considered unnecessary and often difficult, or time-consuming, to quantify precisely.

Not all developmental researchers during this period adopted an information processing approach. Many researchers continued to concentrate on studying developmental sequences of gross motor skills (Halverson et al., 1973) or correlating motor performance outcomes and physiological traits (Malina, 1975). A more interactionist perspective included considering the effect of the environment on the appearance and progression of gross motor skills. This was either from the physical education perspective of how teaching can promote faster progression through “stages of development” (e.g., Halverson et al. 1977) or from the developmental psychology perspective of child-rearing practices that promote the appearance of new skills. A classic example of the latter was Charles Super’s work (Super, 1976) in studying Kenyan babies in a rural setting and comparing them with babies reared in an urban setting using the Bayley scales that were normed in the USA. Super found that rural African babies could sit 3 weeks earlier than could African urban babies who were, in turn, 3 weeks in advance of the American norms. Super argued that these differences could be explained through the child-rearing practices employed in these three groups. Super (1976) also found that African babies were behind the US norms in activities such as crawling, which was not encouraged by the African mothers. This cross-cultural work, as well as earlier studies of infants in institutions such as state hospitals (e.g., White, Castle, & Hein, 1964), who were also behind US norms, strongly illustrated the potential for the environment (e.g., child-rearing practices) to influence the rate of early motor development.

In summary, the Information Processing period was a time when the importance of underlying processes, and specifically perceptual-cognitive processes that control and coordinate movement, was recognized by many studying motor development. Methodologically, it became important to design experiments where independent variables were manipulated with the intent of discovering age-related differential effects that might reveal developing processes that control and coordinate motor skills. The nature of these experiments and the need to tightly control, manipulate and measure variables of movement such as time and distance, resulted in simple movements becoming the staple of most experiments during this period. Although not all embraced information processing components as important to the study of motor development, the overall theoretical framework for all in this period was firmly interactional rather than maturational, and the importance of environmental factors was well acknowledged and studied. A legacy of this period is the focus on studying "cognitive" processes such as perception, decision-making, attention and memory.

Dynamical Systems period (1982-2000*)*

The information processing approach to studying motor development specifically and motor control, in general, was challenged by a dramatically new approach in the early 1980s. We mark the launch of this Dynamic Systems period with the 1982 publication of Kugler, Kelso and Turvey's chapter in Kelso and Clark's edited book, *The Development of Movement Control and Coordination.* This chapter extended Kugler, Kelso, and Turvey's innovative treatise on motor control (Kugler, Kelso, & Turvey, 1980) to the development of "naturally developing systems." This new perspective employed "principles drawn from philosophy, biology, engineering science and, in particular, non-equilibrium thermodynamics, and the ecological approach to perception and action" to understand motor behavior and, in particular, motor skill development (Kugler et al., 1982, p.5).

Following Nikolai Bernstein (Bernstein, 1967), Kugler, Kelso and Turvey (1980) argued that movement cannot be controlled by specific output from the central nervous system (e.g., commands from a motor program) because there are far too many degrees of freedom (joints, muscles, motor units) to control. Rather, behavior is achieved in a self-organizing fashion from internal and external influences (or systems) resulting in functionally specific muscle groups or synergies (they referred to as coordinative structures). These functional muscle synergies emerge from multiple constraints. The constraints can be seen as arising from three sources: 1) the organism itself (both structural and functional); 2) the environment surrounding the organism (including physical and social); and, 3) the task at hand (Newell, 1986).

When reflecting back on previous research periods, both the neuromaturational and information processing perspectives can be critiqued for their limitations in addressing the degrees of freedom problem and also the problem of context-conditioned variability (Bernstein, 1967; Turvey, Fitch & Tuller, 1982). The latter, refers to internal and external sources of constraints that alter the context of a behavior such that the same neural input will produce different behaviors. In addition, neither of these perspectives adequately spoke to the developmental issues of how and why new behaviors emerge (cf., Thelen, Fogel, & Kelso, 1987). At this point in motor development research, the focus was now squarely on "…understanding the changes in motor behavior over the lifespan and the process(es) which underlie these changes" (Clark & Whitall, 1989, p. 194). As always, understanding what was changing was important, but now the "what" was not just on the behavior itself, but the underlying processes that cause changes in motor behaviors, or the "how/why" question. Contrary to prior focus on the central nervous system as the *most* important contributor to changing movement abilities (cf. neuromaturational and information processing approach), the influence of other organismic and/or task and environmental constraints were now considered more fully and led us to discuss this period in our history of motor development as unique and independent of prior and future periods.

Studies by Thelen and her colleagues did much to initially popularize the use of concepts such as “constraints” and “self-organizing” from the dynamic systems approach for motor development. Her work, for example, on the development of walking (see Thelen & Fisher, 1982 and Thelen & Ulrich, 1991, both in Clark et al., this volume) questioned the neuromaturational approach to motor development, which was still the preeminent perspective in medical fields such as physical and occupational therapy. Thelen demonstrated that pre-walking infants had the essential elements of walking (alternating stepping) that only needed the correct supporting constraints (being held on a treadmill), not waiting for “maturation” of the neural pathways, in order to appear (Thelen & Ulrich, 1991). Following principles of non-linear thermodynamics, these findings could be interpreted as an example of a stable system state, the state of walking, that occurs within boundary conditions or constraints within which the walking state can exist without alteration of its form. That is, infant walking exists in a gravitational world, and when the infant has enough motivation, strength and balance control to support it, (artificially induced in the treadmill paradigm) walking will emerge. A change in the stable state occurs when a relevant constraint, called a control parameter, is scaled beyond a critical value, at which point the stable state will undergo a relatively abrupt transition to a new stable state. A classic example is increasing the speed of walking until a transition into running occurs. The concept of a control parameter can explain real-time behavioral change (e.g. transition from walking to running as velocity increases) but does not always explain developmental change (e.g. transition from walking to running over developmental time). In this transition, infants cannot immediately increase speed when they first learn to walk because other constraints need to develop further before they can run.

Thelen (1986) proposed the concept of a “rate-limiting” constraint, which refers to the constraint or control parameter that is the slowest developing component from which a behavior is assembled and a developmental change occurs. Thelen proposed eight potential constraints for the appearance of independent walking including extensor strength, postural control and motivation among others. Based on their own and others research, Thelen & Ulrich (1991) stated that postural control and strength are the two rate-limiters for walking in most typically developing infants. However, motivation might be the rate-limiter for blind infants and environmental conditions might be the rate-limiter for infants growing up where little area to ambulate exists, such as in a jungle. A few researchers followed Thelen’s (Thelen & Ulrich, 1991) methodology of determining changing coordination patterns and rate-limiting constraints. For example, Clark and Phillips (1993) studied the development of intralimb coordination in the first year of independent walking, Whitall and Getchell (1995) studied constraints in the development of running, Ulrich and colleagues (1992; 1995) successfully applied the methodology to the development of walking in Down’s syndrome infants and Corbetta & Thelen (1996) studied the origins of bimanual coordination.

Thelen’s early work and the work of many others in this period typically followed tenants of the Dynamical Systems approach either without specifically testing/developing mathematical models of dynamic systems or by applying dynamical models that were already in the adult motor control literature. For example, repetitive interlimb coordination of finger movements had been modeled as coupled non-linear limit-cycle oscillators by Kelso and colleagues (Haken, Kelso, & Bunz, 1985; Kelso, Holt, Rubin, & Kugler, 1981). Properties of these types of oscillators such as phase-entrainment and stability were subsequently sought in cross-sectional studies of walking (Clark et al., 1988), running and galloping (Whitall, 1989) and a longitudinal study of hopping

(Roberton & Halverson, 1988). In general, it was found that infants and children exploit the dynamic properties of their bodies from an early age but need to fine tune their behavior over time. A few researchers went further and built equations of motion from physical models to test in a developmental context. One example of this approach is a study on infants bouncing in a baby bouncer where the discovery of the ability to use the properties of the spring was described (Goldfield, Kay, & Warren, 1993).

A major methodological consequence of using the Dynamical Systems approach was a return to studying more complex fundamental motor skills such as early walking (Clark, Whitall, & Phillips, 1988) and running/galloping (Whitall, 1989) because reaction time and simple movements did not represent well the complexity of movement in everyday life. Another change from the previous period was the recognition of the importance of both individual and group-designed analyses of behavior. If motor development and the appearance of new functional muscle synergies depends on a variety of constraints, and if the constraints themselves have unique developmental profiles, then it is clearly better to study individuals in depth and frequently across time rather than focus on a few variables in a large group of different-aged subjects on one occasion. This dense, longitudinal approach was put into practice by Thelen, who studied the reaching development of four infants on a weekly basis for one year (Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993). This study showed that even within four infants, there were at least two very different developmental pathways to acquiring a reach.

Studying behaviors as they changed meant that key experiential markers became an alternative to age for group comparisons. That is, individuals with similar amounts (or types) of experience such as crawling or walking behaviors were more likely to reveal similarities and underlying causes of a recent or prospective developmental change than arbitrarily picking different ages. For example, Bell and Fox (1997) looked at experience as a predictor of infant performance holding age constant. That is, they studied 8-month-old infants who had different locomotor experience (i.e., infants without crawling experience and infants with varying amounts of crawling experience) and found that the crawlers performed better on an object permanent task than the non-crawlers.

A complementary perspective during the Dynamical Systems period was the approach referred to as “Ecological”. This approach, derived from psychologists, began much earlier than 1982 (see Gibson & Walk, 1960 in Clark et al., this volume) but Kugler et al. (1982) drew the field’s attention to the parallels with the Dynamical Systems perspective. Essentially, the mutuality of the organism, the environment, and the task brings together the interrelatedness of the action and its context – and thus, the perception of the environment and the task. The mutuality forms a “system” that is ever changing (i.e., dynamic) – hence the Ecological approach formed a critical component of the Dynamical Systems period and motor development researchers began to embrace it.

A basic methodology of the developmental ecological approach during this period involves three related steps. First, perceived features of an object (e.g., a cube) or environment (e.g., slope of ground) are varied by the researcher and the corresponding actions/movements (e.g., grasps or method of traveling) are recorded. This strategy employs the concept of an affordance, which can be defined as the relationship between an object/environment properties and what these afford for the individual given their own organismic constraints. Second, these relationships are quantified with the expectation that changing action patterns will be related to some relevant organismic constraint (e.g., finger-thumb aperture). This quantification includes the identification of critical points corresponding to changes in behavior and optimal points corresponding to stable relationships between the person and the environment. Third, these relationships are compared across chronological age, developmental age or sometimes across abilities within an age. One set of studies from this ecological methodology comes from Newell who demonstrated that infants (Newell, McDonald, & Baillargeon, 1993) and children (Cesari & Newell, 2000) showed similar scaling of grasp configurations to object size as adults. Another set of studies focused on the relationship between infant crawling or walking and environmental constraints such as slopes (Adolph, 1997) and obstacles (Stoffregen, Schmuckler, & Gibson, 1987) or changes in body constraints such as dimensions (Adolph & Avolio, 2000).

A second, related, experimental paradigm involved manipulating or perturbing the sensory information (usually visual or somatosensory) using a variety of methods such as a visual cliff, moving rooms or support surface perturbations. The response to the perturbation allowed the researcher to decide how developed the infant's sensorimotor system was at particular time-points. For example, the development of postural control was investigated through moving room experiments (Bertenthal, Rose & Bai, 1997) and through platform perturbations (e.g., Sveistrup & Woollacott, 1996). The latter paradigm, it should be noted, was not strictly from a dynamic systems perspective but combined elements of perception-action coupling and biomechanical electromyographic analysis.

One further aspect of ecological or perception-action studies has been to ask participants whether they can estimate the relationship between their abilities and a particular set of environmental constraints. In other words, is there intrinsic knowledge of one's body-environment fit (i.e., affordance)? The first and classic study of the subject's ability to know their own body was in adults who were asked to judge if they could climb stairs with various riser heights (Warren, 1984). Adults were accurate in perceiving their action limit or critical point, and their judgment could be predicted by a simple model of leg-length relative to riser height. This supports the hypothesis that perception for the control of action reflects the underlying dynamics of the body-environment system. In an interesting follow-up study, Konczak and colleagues repeated the experiment with older adults and found that, although accurate in their judgements, the critical point for the older adults was predicted by a more complex model that included leg strength and flexibility (Konczak, Meeuwsen, & Cress, 1992). This finding eloquently emphasizes the importance of considering multiple constraints when looking at developmental change in behavior. The study also is an example of a major trend in motor development that occurred during these two decades, namely the extension to a *lifespan approach* to motor development.

While the work of Thelen and others in this period was focused on infants and young children, the end of the 20th century saw a shift to take a "lifespan" perspective on development. In 1970, Goulet & Baltes, two German psychologists proposed to expand the domain of development, which had traditionally been limited to pre-adulthood, to the end of the lifespan (Goulet & Baltes, 1970). The rationale for this expansion was simply that "changes" in behavior, do not just occur in childhood. Developmental change occurs at all ages across the lifespan and, therefore, developmental science should have a common theoretical approach. This argument took root in motor development during the 1980s, in part, because the dynamical systems approach sought common principles of change in all systems of life. Thus, a few motor development researchers began to look at the elderly as well as at infants or children.

One example of a lifespan study was an examination of throwing development – not in children, but in older throwers who were "losing" their skill. The study took place over a two-year period and investigated the seniors' ability to produce a developmentally advanced overarm throwing action in a maximum force condition (Williams, Haywood, & VanSant, 1991). This study is interesting because it essentially combined a methodology from the Descriptive period (developmental component sequences) with an assessment of multiple potential constraints consistent with the dynamical systems approach. The differences in ability observed were related to experiential history (i.e., early sports participation) as well as aging processes and with a stable coordination pattern across many years (Williams et al., 1998). In general, however, taking a developmental and/or a dynamical systems perspective on the changing motor behavior of older adults was not pursued by many researchers except those interested in postural control such as Woollacott and colleagues (e.g., Woollacott, Shumway-Cook & Nashner, 1986, Woollacott, Inglin & Manchester, 1988) and those interested in information processing such as Waneen Spirduso (e.g., Spirduso, 1975; Reilly & Spirduso, 1991).

Finally, there were two research areas that had begun in the Information Processing period that continued to be pursued during the Dynamical Systems period and arguably were influenced by it. First, a group of researchers led by Jerry R. Thomas pursued a more cognitive approach to understanding how children become proficient in performing motor skills within the environmental context of a sport rather than in lab-based experimental contexts. Specifically, they investigated the role of children's knowledge-base in acquiring and refining sport-specific motor skills in games such as basketball (French & Thomas, 1987), tennis (McPherson & Thomas, 1989) and baseball (French, Spurgeon, & Nevett, 1995). An important methodological aspect of this work is the use of an *expert-novice* paradigm whereby researchers strive to understand how experts think and act in order to understand how skillful movement develops. This paradigm explicitly acknowledges that experience may be more important than biological maturation or age per se as noted first by Chi (1978) in a study of memory and chess players. As described earlier, the importance of experience is fundamental to a dynamical systems perspective and this is one example of how information processing and dynamical systems frameworks can appear to overlap or at least co-exist within a set of study questions.

Second, there was an extension of work on cross-cultural comparisons that also shows an overlap of frameworks. Reed and Bril (1996) employed Bernstein's ideas to argue that finding dynamically stable solutions is not an individual matter, but results from "culturally promoted actions." For example, there are many ways to feed oneself, but depending on one's culture, you will use a fork and knife, your fingers, or chopsticks. Others studied the "time table" for the motor milestones of infants. Bril (Bril & Sabatier, 1986) explored the effect of culture (i.e., an environmental constraint) on the onset of upright postures. Hopkins (Hopkins & Westra, 1989) studied the role of infant-rearing handling and maternal expectations on the attainment of the motor milestones of sitting, crawling, and walking. More broadly, these studies also reflect a shift towards studying the development of activities of daily living rather than focusing only on the development of fundamental motor skills that underlie the development of sport-specific skills. For example, Ann van Sant studied changes in movement patterns of children rising from the floor (van Sant, 1988) and age-differences in older adults rising from a bed (Ford-Smith & van Sant, 1993) albeit using methodology from the normative/descriptive period.

In summary, the Dynamical Systems period was a time where both the maturational and information processing theories were challenged by an approach that emphasized principles of physical biology and thermodynamics to explain "change" in a principled fashion – and specifically, developmental change in living systems. Methodologically, studies ranged from those that determined or used dynamic models to those that merely interpreted their data from this perspective. The major changes in study design related to considering the existence of multiple constraints in determining movement and identifying key rate-limiting constraints. Ideally, dense longitudinal studies would be used to determine actual changes and potential rate-limiters and cross-sectional experimental studies would be used to test predictions. Ecological studies, where perceptual information is matched to action using body scaling, were popular in this period and both lifespan and expert-novice paradigms became more prominent. A legacy of this period is evaluating functional (not just fundamental or brain processing) abilities from a multisystem, task/environment perspective using physical principles and including self-organization as a concept.

We would be remiss if we did not mention other motor control "theories" that were conceptually similar to the dynamical systems approach and that were proposed closer to the end of how we defined this period. These theories include the uncontrolled manifold approach (Schöner, 1995), the concept of motor synergies (Tresch et al., 1999), the motor abundance theory (Gelfand & Latash, 1998), and the equilibrium point hypothesis (Feldman, Adamovich, & Levin, 1995). Few of these "theories", however, spawned much motor development research at least in typically developing populations although, at least one, will have some influence in the 21st century.

General Summary and Limitations

In this paper, we revisit the history of motor development research as described by Clark and Whitall in 1989. We propose that their last period, the Process-oriented period, was actually two distinctive periods in our history: the Information Processing period and the Dynamic Systems period. Although we use periods of time to structure our discussion in Part One, it is important to realize that the theoretical perspectives, research questions and methodological approaches that characterize each of these periods partially overlap across subsequent periods and are, arguably, still in existence and influential today.

The limitations of this paper remain the same as Clark & Whitall, 1989. We have restricted our references almost exclusively to work undertaken with the typically developing population that means, for example, that significant research from the medical field on motor development is not included. We also recognize that there are many researchers and studies that we omitted in this narrative review while following the particular thread of identifying major changes in research focus, theories or concepts and methodologies that have changed the manner of motor development research in a meaningful way. We understand that others may not agree with our choice of examples.

In the second part of this review (Whitall et al., this volume), we build upon the history recorded here to take up motor development research into the 21st century using a non-sequential historical approach. We outline the emergence and characteristics of three new and essentially parallel approaches to motor development research, which begun around the turn of the century; we named them: (1) Developmental Systems, (2) Developmental Motor Neuroscience and (3) Developmental Health. We end Part II with thoughts about the future of motor development research.

References

Adolph, K. E. (1997). Learning in the Development of Infant Locomotion. *Monographs of the Society for Research in Child Development, 62(3*), 1-158.

Adolph, K. E., & Avolio, A. M. (2000). Walking Infants Adapt Locomotion to Changing Body Dimensions. *Journal of Experimental Psychology. Human Perception and Performance, 26(3)*, 1148-1166.

Anderson, D.I. (2018). Motor development: Far more than just the development of motor skills. *Kinesiology Review, 7 (2),* 99-114.

Bernstein, N. A. (1967). *The co-ordination and regulation of movement*. New York: Pergamon Press.

Bertenthal, B.I., Rose, J.L. & Bai, D.L. (1997). Perception-action coupling in the development of visual control in posture. *Journal of Experimental Psychology: Human Perception and Performance, 23(6)*, 1631-43.

Borstelmann, L.J. (1983). Children before psychology. In W.Kessen (Ed.) *Handbook of child psychology: Vol. 1. History, theory, and methods* (4^{th} ed., pp. 1-140). New York: Wiley.

Bell, M. A., & Fox, N. A. (1997). Individual differences in object permanence performance at 8 months: Locomotor experience and brain electrical activity. *Developmental Psychobiology, 31*(4), 287-297.

Bril, B., & Sabatier, C. (1986). The cultural context of motor development: Postural manipulations in the daily life of Bambara babies (Mali). *International Journal of Behavioral Development*, *9*(4), 439-453.

Cesari, P., & Newell, K. M. (2000). Body scaling of grip configurations in children aged 6-12 Years. *Developmental Psychobiology, 36(4)*, 301-310.

Chi, M.T.H. (1978). Knowledge structures and memory development. In R.S. Siegler (Ed.) *Children's thinking: What develops?* (pp. 73-96). Hillsdale, NJ: Erlbaum.

Clark, J. E. (1982). Developmental differences in response processing. *Journal of Motor Behavior, 14*(3), 247-254.

Clark, J.E. (2017). Pentimento: A 21st century view on the canvas of motor development. *Kinesiology Review, 6(3),* 232-239.

Clark, J.E., Bardid, F., Getchell, N., Robinson, L., Schott, N., & Whitall, J. (in press). Reflections on motor development research across the 20th century: Six empirical studies that changed the field. *Journal of Motor Learning and Development.*

Clark, J.E., & Phillips, S.J. (1993). A longitudinal study of intralimb coordination in the first year of independent walking: A dynamical systems analysis. *Child Development, 64(4)*, 1143-1157.

Clark, J. E., & Whitall, J. (1989). What is motor development? The lessons of history. *Quest, 41*(3), 183–202.

Clark, J.E., Whitall, J., & Phillips, S.J. (1988). Human interlimb coordination: The first 6 months of independent walking. *Developmental Psychobiology, 21(5*), 445-456.

Clarke, H.H. & Degutis, E.W (1964) Relationships between standing broad jump and varius maturational, anthropometric and strength tests of 12-year-old boys. *Research Quarterly, 35 (3)*, 258-264.

Clarke, H.H., & Glines, D. (2013) Relationships of reaction, movement and completion times to motor, strength, anthropometric and maturity measures of 13-year-old boys. *Research Quarterly, 33 (2),* 194-201.

Clarke, H.H. & Wickens, J.S. (1962) Maturity, structural, strength and motor ability growth curves of boys 9-15 years of age. *Research Quarterly, 33 (1),* 26-39.

Connolly, K. J. (Ed.) (1970). *Mechanisms of motor skill development*. London: Academic Press.

Connolly, K.J. (1973). Factors influencing the learning of manual skills by young children. In R.A. Hinde & J.Z. Stevenson-Hinde (Eds.), Constraints on learning (pp. 337-363). New York: Academic Press.

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

Corbetta & Thelen (1996). The developmental origins of bimanual coordination: a dynamic perspective. *Journal of Experimental Psychology: Human Perception and Performance. 22(2)*, 502-22

Espenschade, A.S. (1963). Restudy of relationships between physical performances of school children and age, height and weight. *Research Quarterly, 34 (2),* 144-153.

Fairweather, H. & Hutt, S.J. (1978). On the rate of gain of information in children. *Journal of Experimental Child Psychology, 26(2),* 216-229.

Feldman, A.G, Adamovich, S.V & Levin, M.F. (1995). The relationship between control, kinematics and electromyographic variables in fast single-joint movements in humans. *Experimental Brain Research, 103 (3),* 440-50.

Ford-Smith, C. D., & VanSant, A. F. (1993). Age differences in movement patterns used to rise from a bed in subjects in the third through fifth decades of age. *Physical Therapy*, *73*(5), 300-309.

French, K. E., Spurgeon, J. H., & Nevett, M. E. (1995). Expert-novice differences in cognitive and skill execution components of youth baseball performance. *Research Quarterly for Exercise and Sport, 66(3),* 194-201.

French, K. E., & Thomas, J. R. (1987). The relation of knowledge development to children's basketball performance. *Journal of Sport Psychology, 9(1)*, 15-32.

Gelfand, I.M., & Latash, M.L. (1998). On the problem of adequate language in motor control. *Motor Control, 2(4)*, 306-13.

Gesell, A. (1928). *Infancy and human growth*. New York: Macmillan.

Gesell, A., & Thompson, H. (1929). Learning and growth in identical infant twins. *Genetic Psychology Monographs, 6,* 1-123.

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

Goldfield, E. C., Kay, B. A., & Warren, W. H. J. (1993). Infant bouncing: The assembly and tuning of action systems. *Child Development, 64(4)*, 1128-1142.

Goulet, L. R., & Baltes, P. B. (Eds.) (1970). *Life-span developmental psychology: Research and theories*. New York: Academic Press.

Haken, H., Kelso, J.A.S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51(5)*, 347-356.

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

Halverson, L. E. (1966). Development of motor patterns in young children. *Quest*, *6*(1), 44-53.

Halverson, L.E., Roberton, M.A., Safrit, M.J., & Roberts, T.W. (1977). Effect of guided practice on overhand-throw ball velocities of kindergarten children. *Research Quarterly, 48(2),* 311-318.

Hay, L. (1979). Spatial-temporal analysis of movements in children. *Journal of Motor Behavior, 11(3)*, 189-200.

Hellebrandt, F. A., Rarick, G. L., Glassow, R., & Carns, M. L. (1961). Physiological analysis of basic motor skills: 1. Growth and development of jumping. *American Journal of Physical Medicine & Rehabilitation*, *40*(1), 14-25.

Hopkins, B., & Westra, T. (1989). Maternal expectations of their infants' development: Some cultural differences. *Developmental Medicine & Child Neurology*, *31*(3), 384-390.

Keele, S.W., & Summers, J.J. (1976). The structure of motor programs. In George E. Stelmach (Ed.), *Motor control: Issues and trends* (pp. 109-142). NY: Academic Press

Kelso, J.A.S., & Clark, J.E. (Eds.) (1982). *The development of movement control and coordination*. New York: John Wiley.

Kelso, J. A., Holt, K. G., Rubin, P., & Kugler, P. N. (1981). Patterns of human interlimb coordination emerge from the properties of non-linear, limit cycle oscillatory processes: Theory and data. *Journal of Motor Behavior*, *13(4)*, 226-261.

Kelso, J. S., & Norman, P. E. (1978). Motor schema formation in children. *Developmental Psychology*, *14*(2), 153-156.

Konczak, J., Meeuwsen, H. J., & Cress, M. E. (1992). Changing affordances in stair climbing: The perception of maximum climbability in young and older adults. *Journal of Experimental Psychology. Human Perception and Performance, 18(3)*, 691-697.

Kugler, P. N., Kelso, J. A., & Turvey, M. T. (1980). On the concept of coordination structures as dissipative structures: I Theoretical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 3-47). New York: North-Holland.

Kugler, P. N., Kelso, J. S., & Turvey, M. T. (1982). On the control and coordination of naturally developing systems. In J. A. S. Kelso & J. E. Clark (Eds.), *The development of movement control and coordination* (pp. 1-78). London: John Wiley.

Malina, R.M. (1975). Anthropometric correlates of strength and motor performance. *Exercise & Sports Science Reviews*, *3*,249-74.

McGraw, M.B. (1935) *Growth: A study of Jimmy and Johnny*. NY: Appleton-Century.

McGraw, M. B. (1940). Neuromuscular development of the human infant as exemplified in the achievement of erect locomotion. *The Journal of Pediatrics*, *17*(6), 747-771.

McPherson, S. L., & Thomas, J. R. (1989). Relation of knowledge and performance in boys' tennis: Age and expertise. *Journal of Experimental Child Psychology, 48(2*), 190-211.

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341-360). Boston, MA: Martinus Nijhoff.

Newell, K.M., & Kennedy, J.A. (1978). Knowledge of results and children's learning. *Developmental Psychology, 14(5)*, 531-536.

Newell, K. M., McDonald, P. V., & Baillargeon, R. (1993). Body scale and infant grip configurations. *Developmental Psychobiology*, *26*(4), 195-205.

Preyer, W. T. (1909a) The mind of the child. Part I: the senses and the will. New York: Appleton (Original work published in German, 1881-1882a).

Preyer, W. T. (1909b) The mind of the child. Part II: the development of the intellect. New York: Appleton (Original work published in German, 1881-1882b).

Reed, E.S. & Bril, B. (1996). The primacy of action in development. In M.L. Latash & M.T. Turvey (Eds.), Dexterity *and its development* (pp. 431-451). NJ: Lawrence Erlbaum.

Reilly, M. A., & Spirduso, W. W. (1991). Age-related differences in response programming. *Research Quarterly for Exercise and Sport*, *62*(2), 178-186.

Ridenour M. (1974). Influence of object size, speed and direction on the perception of a moving object. *Research Quarterly, 45(3)*, 293-301.

Robinson, L.E. (2018). Motor development, a field with a bright future. *Kinesiology Review, 7(2)*, 115-122.

Roberton, M. A., & Halverson, L. E. (1988). The development of locomotor coordination: Longitudinal change and invariance. *Journal of Motor Behavior, 20(3*), 197-241.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, *82*(4),
225-260.

Schöner, G. (1995). Recent developments and problems in human movement science and their conceptual implications. *Journal of Ecological Psychology, 7(4*), 291-314.

Shinn, M. (1900). *Biography of a baby*. Boston: Houghton Mifflin.

Singer, R.N., (1968). Interrelationship of physical, perceptual-motor and academic achievement variables in elementary school children. *Perceptual and Motor Skills, 27*, 1323-1332.

Smith, J.A. (1956). Relation of certain physical traits and abilities to motor learning in elementary school children. *Research Quarterly, 27 (2)*, 220-228.

Spirduso, W. W. (1975). Reaction and movement time as a function of age and physical activity level. *Journal of Gerontology*, *30*(4), 435-440.

Stoffregen, T. A., Schmuckler, M. A., & Gibson, E. J. (1987). Use of central and peripheral optical flow in stance and locomotion in young walkers. *Perception, 16(1)*, 113-119.

Super, C. M. (1976). Environmental effects on motor development: The case of African infant precocity. *Developmental Medicine and Child Neurology, 18*, 561-567.

Sveistrup H., & Woollacott MH (1996). Longitudinal postural responses in infants. *Journal of Motor Behavior, 28 (1)*, 58-70.

Thelen, E. (1986). Development of coordinated movement. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of motor coordination and control* (pp. 107-124). Boston, MA: Martinus Nijhoff.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: Mapping intention and intrinsic dynamics. *Child Development, 64(4)*, 1058-1098.

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

Thelen, E., Fogel, A., & Kelso, J.A.S. (1987). Self-organizing systems and infant motor development. *Developmental Review, 7(1),* 39-65.

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.

Thomas, J. R. (1980). Acquisition of motor skills: Information processing differences between children and adults. *Research Quarterly for Exercise and Sport*, *51*(1), 158-173.

Thomas, J.R., Mitchell, B., & Solomon, M.A. (1979). Precision knowledge of results and motor performance: Relationship to age. *Research Quarterly, 50(4)*, 687-698.

Tresch, M.C., Salteil, P., & Bizzi, E. (1999). The construction of movement by the spinal cord. *Nature Neuroscience*, *2(2)*, 162-167.

Turvey, M. T., Fitch, H. L., & Tuller, B. (1982). The Bernstein perspectives: I. The problems of degrees of freedom and context-conditioned variability. In J.A.S. Kelso (Ed.), *Human motor behavior* (pp. 239-252). NJ: Lawrence Erlbaum.

Ulrich B.D., Ulrich, D.A., & Collier D.H. (1992). Alternating stepping patterns, hidden abilities of 11-month-old infants with Down syndrome. *Developmental Medicine and Child Neurology*. *34*(3), 233-239.

Ulrich B.D., Ulrich, D.S., Collier, D.H., & Cole E.L. (1995). Developmental shifts in the ability of infants with Down syndrome to produce treadmill steps. *Physical Therapy. 75(1),* 14-23.

VanSant, A. F. (1988). Age differences in movement patterns used by children to rise from a supine position to erect stance. *Physical Therapy*, *68*(9), 1330-1338.

Warren, W. H., Jr. (1984). Perceiving affordances: visual guidance of stair climbing. Journal of *Experimental Psychology: Human Perception Performance, 10(5*), 683-703.

Whitall, J. (1989). A developmental study of the interlimb coordination in running and galloping. *Journal of Motor Behavior, 21(4),* 409-428.

Whitall, J., & Getchell, N. (1995). From walking to running: applying a dynamical systems approach to the development of locomotor skills. *Child Development*, *66*(5), 1541-1553.

Whitall, J., Bardid, F., Getchell, N., Pangelinan, M. M., Robinson, L. E., Schott, N., & Clark, J.E. (in preparation). Motor development research. II: The first two decades of the 21st Century shaping our future. *Journal of Motor Learning and Development.*

White, B. L., Castle, P., & Held, R. (1964). Observations on the development of visually-directed reaching. *Child Development*, *35*, 349-364.

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.

Williams, H.G., & DeOreo, K. (1980). Perceptual-motor development: A theoretical overview. In C.B.Corbin (Ed.), *A textbook of motor development* (2nd ed., pp. 136-147). Dubuque, IA: Wm, C. Brown.

Williams, K., Haywood, K., & VanSant, A. (1991). Throwing patterns of older adults: A follow-up investigation. *International Journal of Aging and Human Development, 33(4)*, 279-294.

Williams, K., Haywood, K., & VanSant, A. (1998). Changes in throwing by older adults: a longitudinal investigation. *Research Quarterly in Exercise and Sport, 69 (1)*, 1-10.

Winther, K.T., & Thomas, J.R. (1981). Developmental differences in children's labeling of movement. *Journal of Motor Behavior*, *13(2)*, 77-90.

Witte, F. (1982). Relation of kinesthetic perception and a selected motor skill for elementary school children. *Research Quarterly, 36(3*), 476-484.

Woollacott, M.H., Shumway-Cook A., & Nashner, L.M. (1986). Aging and posture control: changes in sensory organization and muscular coordination. *International Journal of Aging and Human Development*, 23(2), 97-114.

Woollacott M., Inglin B., & Manchester, D. (1988). Response preparation and posture control. Neuromuscular changes in the older adult. *Annals of the New York Academy of Science. 515*(1), 42-53.