Motor development research: II. The first two decades of the 21st century shaping our future

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Abstract

In Part I of this series (Whitall et al., this issue), we looked back at the 20th century and re-examined the history of Motor Development research described in Clark & Whitall's 1989 paper "What is Motor Development? The Lessons of History". We now move to the 21st Century, where the trajectories of developmental research have evolved in focus, branched in scope, and diverged into three new areas. These have progressed to be independent research areas, co-existing in time. We posit that the research focus on dynamical systems at the end of the 20th century has evolved into a Developmental Systems approach in the 21st century. Additionally, the focus on brain imaging and the neural basis of movement have resulted in a new approach, which we entitled, Developmental Motor Neuroscience. Finally, as the world-wide obesity epidemic identified in the 1990's threatened to become a public health crisis, researchers in the field responded by examining the role of motor development in physical activity and health-related outcomes; this research area, we refer to as the Developmental Health approach. The glue that holds these research areas together is their focus on movement behavior as it changes across the lifespan.

Keywords: motor development, history, developmental systems, developmental motor neuroscience, developmental health

Three decades ago, Clark and Whitall (1989) wrote a paper in which they characterized the history of motor development research from the early baby biographies of the 18th century to the process-oriented approach of the 1980s as represented by four distinct eras or periods. In the accompanying paper, Part I, (Whitall et al., this volume), Whitall, Clark and colleagues updated the 1989 paper to include the advances made through the end of 20th century. In the current paper (Part II), we turn to the 21st century and ask ourselves: Where is motor development research today? How has it evolved since the end of the 20st century? What might be the field's developmental trajectory into the future?

Unlike the 20th century, where we saw successive developing periods, at this point in the 21st century, we do not yet see a series of successive "periods." In contrast, during the last decade of the 20th century, three parallel, and relatively independent, areas of motor development research have emerged and dominated the early 21st century research landscape. In the current paper, we characterize these research areas by their theoretical perspectives, research questions, and methodological approaches. The first of these approaches, we have titled *Developmental Systems*, the second as *Developmental Motor Neuroscience*, and, the third, *Developmental Health*. While these approaches occasionally may converge around a specific research problem, they are distinct scientific approaches. Please note that as we present the three approaches here, the order in which they are discussed is arbitrary.

Developmental Systems Approach

In 2000, Thelen published an essay in the *International Journal of Behavioral Development* entitled, "Motor development as foundation and future of developmental psychology," in which she argued that understanding motor development is critical to an understanding of development as a whole. As she had theoretically and empirically argued so persuasively throughout her career, reciprocity exists between brain and body; therefore, developmental research must explore how all the systems interact to produce behavioral development. Thelen's description of interacting developing systems characterizes what we refer to as the "developmental systems" approach to motor development research. Those employing this approach emphasize looking at all developing systems – not as unique entities, but as interacting systems (e.g., cognitive, perceptual, linguistic, motor, etc.) from which behavioral development emerges. For those who followed Thelen's writings, a 'developmental systems' approach seems a natural consequence of her dynamic systems approach (see Whitall et al., this volume).

To describe, explain, and to promote both change within an individual and between individuals across the life course is the goal of those studying motor development. For those taking a developmental systems approach, a focus *only* on motor behavior is insufficient. Rather the approach sees the integration of all the developing systems (e.g., motor, cognitive, physiological, etc.) as they change together across the lifespan in the ecology of the developing human as a distinct and important perspective to understanding human development.

In a recent special issue, *WIREs Cognitive Science* presented a collection of papers addressing the "unifying" theoretical perspective, named, "developmental systems." The editors (Blumberg et al., 2017) argue, like Thelen, that this perspective offers a broad framework for thinking about human development, both typical and atypical, at multiple levels of analysis (from the molecular to the behavioral), and across different time scales. This approach also has been used to characterize development, heredity, and evolution along with their interrelatedness to explain human development (Griffiths & Gray, 2005; Johnston, 2010; Oyama et al., 2001).

From the specific perspective of motor development, research questions are posed to ask how developing motor behavior (e.g., the ability to locomote) reciprocally affects and is affected by other developing systems. A wonderful illustration of this research can be seen in the work of Campos and his colleagues (2000) as encapsulated in the title of their paper, "travel broadens the mind." As infants themselves navigate their environment, the world literally opens up to them "expanding" their minds (Anderson et al., 2013). And, as others have demonstrated, when infants move and explore greater spaces, or interact with more objects and other people, they expand their perceptual-cognitive capabilities (Corbetta, Friedman, & Bell, 2014; Thurman & Corbetta, 2017).

Iverson (2010) makes a similar argument about changes in motor skills, such as stable upright posture, independent locomotion, and object manipulation, that open the world to infants and directly and indirectly promote the development of communicative and language skills. In another study, "Sit to talk," the authors report that as infants begin sitting, this new behavior may open doors to increased language opportunities and future language achievement (Libertus & Violi, 2016). Indeed, two studies looking at walk onset, one involving a longitudinal and the other an age-held-constant design, found that walking onset was associated with significant improvements in receptive and productive language (Walle & Campos, 2014).

While much of the work from a developmental systems perspective has focused on infant development, this approach also is being used by those researching older children. For example, a dramatic finding on the interaction of motor and cognitive development is reported by Bornstein and colleagues (2013). In their 14-year longitudinal study of over 300 US children, the motor-exploratory competence of 5-month-old infants was related to higher academic achievement at 14 years of age. The Finnish Jyvaskyla Longitudinal Study also reported similar conclusions, namely that infants with more advanced motor development in the first year had larger vocabularies at 3 and 5 years and were better readers at 7 years (Viholainen et al., 2006). Researchers in Australia also found a relationship between early gross motor development (from 4 months to 4 years) and later working memory and processing speed of school-age children (6 to 11 years) (Piek et al., 2008). Others have argued that tailoring physical games and other physical activity interventions can be used to promote cognitive development at the same time benefit motor skill development and promote health through physical activity (Alvarez-Beuno et al., 2017; Pesce et al., 2016). In addition, Pesce and her colleagues have argued for the interplay between motor creativity and creative thinking (Scibinetti et al., 2011). Indeed, McClelland and Cameron (2019) argue that executive function and motor skills "developing together" should be studied as a unit to better understand their bidirectional and reciprocal development. Such studies could enhance school readiness and achievement both in the motor and cognitive domains.

As Viholainen and colleagues (2006) found in their study of early motor development, reading and language, those infants at risk for dyslexia demonstrated a relationship between their slow motor development as infants and their later reading speed and language development. This relationship between motor and cognitive performance can also be seen in specific groups such as children with Developmental Coordination Disorder (DCD) or Down Syndrome (DS). Several studies have shown that children with DCD sometimes have major problems with tasks that require executive functions (e.g., working memory, inhibition, cognitive flexibility, dual task tasks) (Schott, 2019; Wilson et al., 2017), while children with Down Syndrome show clear limitations in motor skills (Schott & Holfelder, 2015). In addition, Galloway and colleagues have expanded and translated their research to the development of children with mobility issues, examining the effect of early powered mobility devices on cognitive and social development (Feldner, Logan & Galloway, 2016; Logan et al., 2018).

As this developmental systems perspective has emerged and gained traction as a research approach, it should not be surprising to find that for the first time in its long history, the *Annual Review of Psychology* included a review that focused on motor development (Adolph & Hoch, 2019). The review's authors articulate well the systems approach to the development of behavior where motor development is fundamentally interrelated with understanding "behavioral" development. This relationship characterizes motor development as embodied, embedded, enculturated, and enabling (Adolph & Hoch, 2019). That is, the development of motor behavior is embodied and embedded – embodied in our physical structure and embedded in our physical and socio-cultural environments. Our movements are enculturated by social influences and those practices that are culturally promoted. Moreover, as we move, we enable new opportunities for environmental interactions that promote learning new behaviors. Our developing movements are surrounded by and resulting from many systems – which themselves may be developing.

Similarly, the latest *Advances in Child Development and Behavior (vol. 55)* focused on the "perception-action system" as a model system for understanding development (Plumert, 2018). The volume illustrates the landscape of developmental systems research with chapters, for example, on how perception-action fosters infants' exploring and selecting reaching skills (Corbetta et al., 2018), spatial orientation for object fitting (Lockman et al., 2018), and, dynamic affordances for road-crossing (Plumert & Kearney, 2018).

In summary, the Developmental Systems approach appears to be a legacy of the earlier Dynamic Systems Approach with an emphasis on functional motor skill development and on demonstrating the influence of mutually developing systems. While the methodologies of dynamic systems may be employed (Molenaar et al., 2013) in the developmental systems approach, these methodologies are not solely based on "dynamic principles," but often employ observational and correlational descriptions that are micro-genetic or longitudinal in nature. Many of these studies have focused on early development and are often undertaken by developmental psychologists, with a few studies using this kind of approach with older children. No studies seem to be explicitly using this approach across the lifespan. As will be seen later, examining the relationship between developing motor skills and developing cognitive skills is also a part of the other two contemporary research approaches (i.e., developmental motor neuroscience and developmental health); however, they come at the issues with different questions and perspectives and using different methodologies. For those seeking a broad approach to development, where motor development is an integral part of the more global approach to development, the Developmental Systems approach offers a scientific umbrella within which to situate one's questions.

Developmental Motor Neuroscience Approach

In 1990, the United States declared 1990-1999 to be the "decade of the brain" focusing attention on the importance of brain research (Goldstein, 1994). Increased funding from the US National Institutes of Health (NIH) resulted in marked growth in neuroscience research that included research on developmental questions and questions focused on motor development. By the start of the 21st century, the Developmental Motor Neuroscience approach had taken hold; a period we characterize as one that unites the study of motor development with the advanced technical methodologies and models of neuroscience, and addresses research questions surrounding how the brain controls movement across developmental time.

Two major complementary and parallel research clusters are observed within the Developmental Motor Neuroscience approach. The first cluster is comprised of researchers who seek to understand the development of cognitive-motor behavior by capturing and analyzing neural activity using the expanding sophisticated imaging tools of neuroscience (e.g., fMRI, EEG, fNIRS). The second research cluster includes those researchers who employed neuromotor computational models and paradigms of motor control and motor learning (e.g., adaptation paradigm) to address developmental issues in motor behavior.

Today's imaging techniques provide an unprecedented insight into the functioning of the human brain. In the *first research cluster* of the Developmental Motor Neuroscience Approach, we see the findings from neuroscience, such as the organization of functions in widely ramified networks and the flexibility of the adult brain, employed to understand healthy and impaired motor development. Functional imaging methods can be divided into two classes: electrophysiological and hemodynamic methods. Electrophysiological methods measure the activity of nerve cells relatively directly, i.e., measuring action potentials. Hemodynamic methods make use of a secondary effect of neuronal activity, namely the increased metabolic turnover of active nerve cells. The electrophysiological methods include: electroencephalography (EEG); event-related potentials (ERP); and, magnetoencephalography (MEG). The hemodynamic procedures include: positron emission tomography (PET); functional magnetic resonance imaging (fMRI); single-photon emission computed tomography (SPECT); and optical imaging or near infrared spectroscopy (NIRS) and functional near infrared spectroscopy (fNIRS). In general, electrophysiological methods have good time resolution but a poor spatial resolution, while hemodynamic methods have good spatial resolution but poor time resolution. Due to technical developments, however, the respective disadvantages have become smaller and smaller.

An early study by Taub and his colleagues (Elbert et al., 1995) demonstrates the potential of neuroimaging for motor development. Using MEG, the researchers recorded brain activity from the fingertips of string players (e.g., violinists, cellists, and a guitarist) and those who did not play a string instrument. For the first time, the effects of playing a string instrument could be seen in the musicians' brains. The recordings demonstrated that the string players had greater cortical representation in the somatosensory cortex than the control group for the fingers they used to depress the strings. For those studying motor development, the ancillary findings from this study revealed an even more important insight: namely, the amount of cortical reorganization in the brain's finger representation was correlated with the age at which the string players began to play their instruments. Here, for the first time, was clear evidence through neural imaging of the brain's neuroplasticity in response to practicing a motor skill in childhood.

Similarly, in the late 20th century, there were studies of young children that demonstrated age-related differences in cortical activity for reaching actions. One of the earliest studies that characterized differences in the time-course of brain activity during the preparation and performance of skilled motor behavior in children was conducted by Chiarenza and colleagues (1983). They found that the location, consistency, and shape of the neural response was similar to that of adults in 10- to 13-year-old children; but this was not the case for the 8- to 9-year olds. Subsequently, these results were replicated using a similar button-press task over a larger age range (Bender et al., 2005; Chiarenza, Villa, & Vasile, 1995).

As the 21st century began, a growing number of studies emerged using MRI-based neuroimaging tools revealing changes in the brain across the lifespan that are associated with developmental changes across a broad range of motor behaviors. For example, to evaluate the relationship between structural changes in the brain as it relates to motor development, Pangelinan and her colleagues (2011) used a large longitudinal database of pediatric MRI and behavioral measures available through the NIH (NIH Study of Normal Brain Development, Evans, et al., 2006). Structural development of brain regions traditionally associated with motor coordination and control (e.g., cerebellum and basal ganglia) were associated with cognitive performance. Moreover, motor and cognitive development were related at the behavioral level. Together, Pangelinan and colleagues' findings provide support for a fundamental interrelationship between cognition and motor skills at both the behavioral and neural levels, which emerges during childhood. Indeed, Morita and colleagues (2016) argue that since significant changes occur from birth to adult in both motor and cognitive behavior and CNS structure, it is important that these be investigated concurrently, an argument echoed by those from the Developmental Systems approach.

Several studies have examined functional changes in the brain using fMRI and how these changes related to motor development. Thomason and colleagues (2018) examined resting state functional connectivity of the sensorimotor networks during prenatal development (during 2nd and 3rd trimester). They found that greater functional connectivity was related to more advanced motor skills at 7 months of age. Similar patterns were observed by Marrus and colleagues (2018) in older infants. They examined functional connectivity of motor networks in the brain and found that as infants developed upright locomotion and other motor skills between 12 and 24 months, a cross-age shift in higher-order cognitive processes (e.g., the dorsal attention, posterior frontoparietal and cingulo-opercular networks) occurred.

Evidence for an interrelationship between motor and cognitive functions at the brain level also has been observed in young children. These studies suggest that the development of motor behaviors may be necessary for the development of cognitive skills like reading and language. As an illustration, James and Engelhardt (2012) studied 4-5 year olds tracing, drawing, and typing letters and shapes and found that brain regions for reading were only activated for letters after they wrote the letters not typed them. The authors suggest that handwriting is important for the early recruitment of letter processing, a skill used in reading. This finding has significance for the trend to reduce handwriting skills in favor of typing skills.

The study of perception and its relationship to action, in infants, has employed EEG recordings, for example, to measure the brain signals (e.g., mu-wave or mu rhythm). They show a strong relationship between an infant's action experience (i.e., crawling) and the perception of others performing that action (van Elk et al., 2008). In addition, EEG measures have shown infants' growing ability to predict forthcoming actions by others (Southgate et al., 2009). Gonzalez and his colleagues (2016) highlight the importance of utilizing EEG power (i.e., reflecting the electrical activity of a particular group of neurons, providing a measure of activity within a cortical region), coherence (measure of interconnection between regions), and mu desynchronization (motor experience-dependent electrical pattern) to understand the underlying neural mechanisms of motor cascades in the social and cognitive development of infants. EEG has also been used to examine the electrocortical dynamics during goal-directed arm reaching in children. Pangelinan and colleagues (2010) characterized this relationship in 6- and 10-year old children and adults. Their results demonstrated that the electrocortical dynamics (i.e., EEG in the frequency and time domains) reflected age-related differences in the quality of children's motor planning and performance of goal-directed arm movements.

One of the drawbacks of using fMRI and EEG to examine motor development is that both techniques are highly sensitive to motion artefacts. For example, fMRI requires individuals to lie motionless in the MRI scanner with their head stabilized. Movement is therefore restricted to simple motor tasks such as finger tapping that do not require head movement or upright posture (DeGuio et al., 2012; Turesky et al., 2018). EEG is very sensitive to movements as well although it has a number of techniques available to reduce artefacts. Recently, researchers of motor development have begun to use an emerging, non-invasive brain imagining technique, functional near infrared spectroscopy (fNIRS) as it does not have the same limitations found with fMRI and EEG imaging (Gervain et al., 2011). fNIRS uses near infrared light to penetrate into the cortex of the brain and detect changes in concentrations of oxygenated and deoxygenated between within specific superficial brain regions, indirectly indicating neural activity. fNIRS provides a quantitative temporal assessment of brain function that can be used to monitor brain responses while participants sit, stand, tap or even walk, unlike other technologies that are highly sensitive to movement artefacts. Thus, the use of fNIRS has opened the door to observing behaviors and populations that have presented considerable challenges in using traditional neuroimaging techniques (Vanderwert & Nelson, 2014). Additionally, the layers of the scalp and skull of young children are still thin, providing better conditions for measuring cerebral blood flow changes. Due to these advantages, researchers have used fNIRS, for example, to better understand task-related brain activity in infants reaching and walking (e.g., Nishiyori et al., 2016), in typically developing children (Lai et al., 2020; Liang et al., 2016; Mazzoli et al., 2019), and children with disabilities such as developmental coordination disorder (e.g. Caçola et al., 2018; Plumb et al, in press), and autism (e.g., Getchell & Liang, 2018; Kaur et al., 2018). One of the disadvantages of fNIRS is that only superficial regions of the brain (4-5mm) can be examined. Since each neuroimaging technique has its advantages and disadvantages, integration of two or more methods within a study would strengthen future studies.

Beyond these neuroimaging approaches, another way in which to study brain function is to stimulate specific regions of the cerebral cortex and measure its effect on more overt behavior. For example, transcranial magnetic stimulation (TMS) is one method in which brief high-intensity magnetic fields are used to stimulate corticospinal neurons and measure the latency and magnitude of the motor-evoked potentials as well as muscular activation. This technique has been used to describe the neuromotor functioning of the corticospinal tract from 2 months of age through 30 years (Fietzek et al., 2000). They found that the maturation of the corticospinal tract appeared to be complete during late childhood ahead of the acquisition of the related motor performance measures, which continued into adulthood. Both TMS and a similar but newer technique, transcranial direct current stimulation (tDCS), can be used to stimulate the brain. For example, tDCS has been effective in enhancing children's motor learning (Ciechanski & Kirton, 2017). Importantly, these techniques could be used with children who have movement disorders that impair their learning of motor skills.

The *second research cluster* in the Developmental Motor Neuroscience area focuses on adopting the concepts and methodology of computational neuroscientists who believe that we can model motor control through a combination of engineering and neuroscience principles. The approach is sometimes known as a *control-theoretic approach* (for a review see Jordan & Wolpert, 1999; Wolpert, 1997). Unlike the dynamic systems theorists who tend to look for general dynamic principles rather than specific mechanisms, these scientists returned to constructing biophysical models of putative underlying processes involving feedforward and feedback mechanisms similar to the information processing approach (see Whitall, et al. this volume). This time, however, the models have an engineering or neuroanatomical basis or both. Also, unlike the developmental systems approach, the models tend to differ according to the task (e.g., balance vs. reaching) and within a particular task since each scientist tends to build their own heuristic model.

One model proposed uses the concept of an "internal model" that learns a set of sensorimotor relationships that enable the performer to adapt to new situations (Miall & Wolpert, 1996). An experimental paradigm that demonstrates this principle is the "adaptation" paradigm. For example, in a visual-motor version of this paradigm, the subject watches a cursor move on a computer screen which reflects the individual's drawing a line with a stylus on a digitizing tablet. Participants move from a central home plate to targets placed around the home plate like numbers on a clock face. Subsequently, the relationship between the movement and the visual feedback is altered by rotating the feedback by 45˚, for example. When the subject starts moving towards the next target using the initial plan that worked successfully before the rotation, they see the visual discrepancy between what they felt would be the right move and what their visual feedback is telling them. Eventually, after many practice trials, the subject learns the new visual-motor relationship as demonstrated by more accurate lines to the targets. However, to "prove" that this new relationship has been learned, the rotation is turned off and the "normal" relationship is re-instated to see if the subject shows an "after effect." This "after effect" results from rotated action persevering when the task returns to the 'typical' visuomotor relationship. The existence of the after effect demonstrates that the new visual-motor relationship was indeed learned, at least temporarily. However, after effects typically wear off after a short time, as the learning is not permanent. A similar paradigm is used to disturb the relationship between force-production and arm movements by altering the force-field dynamics.

Both the visual-motor (Bo et al., 2006; Ferrel-Chapus et al., 2002) and the force-field (Konczak et al., 2003) paradigms have been used with children across age groups and compared with the results from adults. Taken together, these studies found that children as young as 4 years of age can adjust trial to trial to the new relationship, but they do not necessarily learn the transformed sensorimotor maps as demonstrated by after effects unless they are given a much larger number of trials than adults require. In general, younger children are less accurate in their movements and adapt more slowly suggesting more experience in the new environment is necessary for children to fine-tune their "internal model" (Contreras-Vidal et al., 2005; Kagerer & Clark, 2014). By 11 years of age, children differed only slightly from adults, but were still not quite adult-like (Ferrel-Chapus et al., 2002). A critique of this work is that the motor skills under investigation are not those used in everyday life and may include distortions of sensorimotor coordination that are themselves not typically experienced in everyday living. Consequently, some developmental researchers have begun to incorporate skills and adaptations that are more realistic; for example, the sensorimotor transformations needed to map a computer mouse to the action on the computer screen (Bo et al., 2006).

There are several other groups doing research that could be classified within the developmental motor neuroscience approach. For example, how do infants, followed longitudinally, between birth and four months develop the ability to control their head posture and movements during the tracking of a visual object (e.g., Lima-Alvarez et al., 2014)? Similarly, how do children develop the ability to coordinate clapping and walking (Getchell & Whitall, 2003) or coordinate their reach to grasp movements (Schneiberg et al., 2002)? These types of studies of neuromotor control are largely observational and use kinematic analysis to demonstrate changes in motor units or coordination that typically become less variable across age. A deeper approach to studying variability uses the uncontrolled manifold hypothesis (Scholz & Schöner, 1999) developed within the dynamical systems perspective in the late 90's (see Whitall et al., this volume). This hypothesis explains how the natural variability of movement may be a result of (good) variability that does not affect the goal of a task but also (bad) variability that does affect the goal of a task. Developmentally, this can be used to determine how and when the good variability overtakes the bad variability to produce a more skillful movement. This methodology has been used, for example, to study childrens' postural control in standing (Wu et al., 2009) and in manual pointing (Golonia et al., 2018).

Other studies go further in looking at underlying processes by probing the development of sensorimotor integration after adding, removing, or manipulating visual, auditory and/or proprioceptive input and measuring the resulting behavior. For example, independently sitting infants of four developmental groups were provided with varying amplitudes of visual motion in a virtual room allowing researchers to track the early development of visual-postural entrainment and sensory re-weighting (Chen et al. , 2016). This specific line of research has been extended across childhood and adulthood (cross-sectional) and includes assessing multi-sensory weighting (Bair et al., 2007). A general conclusion from this work has been that in the control and coordination of sensory-motor development, intra-sensory development occurs before inter-sensory development. These studies have specifically used models from a contro-theoretical perspective for their theoretical framework.

In contrast, to the perspectives mentioned above, a recent study, that deserves mention, is observational and descriptive even though it describes an underlying process. Konczak and his colleagues (Holst-Wolf et al., 2016) used a technically sophisticated method of measuring proprioceptive acuity in forearm movements. The study involved 308 children (5-17 years old) and 26 young healthy adults (18-25 years old). In addition to the unusally large sample size, albeit cross sectional, this study is notable for providing a developmental landscape, against which children with impairments can be compared. Tying motor development research to medical conditions is a useful direction and much of the work from researchers using a behavioral motor neuroscience approach has been accomplished (and funded) in conjunction with investigating special populations of children who are not typically developing. The most common populations studied are children with Developmental Coordination Disorder (e.g., Adams et al., 2014) and Down's syndrome (e.g., Smith et al., 2011) but there are many others. Since such populations may have defined brain deficits, these comparative investigations may provide insight into underlying brain processes for typical development as well as insights for rehabilitation.

In summary, the Developmental Motor Neuroscience approach comprises two research clusters that focus on the role of the brain and understanding its relationship to movement control. Methodologically, one group uses technological advances for neurological assessment and the other group largely, but not completely, uses conceptual advances from those who model control of movement as an engineering problem with some recognition and incorporation of knowledge about how various parts of the brain combine to control movement. Motor development researchers have embraced both groups' methodologies, but the costs of using imaging techniques, in particular, means that most research is not longitudinal nor employs large samples. The advent of fNIRS technology, however, is especially exciting because it lends itself well to assessing a broader range of naturalistic brain-behavior relationships in children. Finally, both research groups have embraced comparing those typically developing with those who are atypically developing. Both groups also have turned their attention to the other end of the lifespan, expanding the trend that began during the 1980's (see Whitall et al., this volume). Unfortunately most of this work is also combined with populations, such as individuals with Parkinson's disease or those who have experienced a stroke. The emphasis has been on providing age-gender matched controls and not on how non-disabled, typically developing individuals lose their motor skills with increasing age. Further, few of these studies probe the antecedent-consequent relationships across the lifespan. Indeed while not true of all those studying aging adults, many would not describe themselves as developmental researchers. An example of a developmental study of aging is a study on motor imagery focused on when this ability begins to deteriorate in older individuals as well as the mediating effect of a possible decline in working memory (Schott, 2012).

Developmental Health Approach

At the turn of the 21st century, the US Surgeon General (Office of the Surgeon General, 2001) issued a "call to action" to prevent and decrease the prevalence of overweight and obesity in the US. The increasing levels of childhood obesity in the last decades of the 20th century were alarming (Troiano & Flegal, 1998). Indeed, the Centers for Disease Control and Prevention reported that approximately 20.6% of all children between 12 and 19 years of age were overweight (Centers for Disease Control and Prevention, 2019). Preventive approaches focused on both energy intake (i.e., nutritional components) and energy expenditure (i.e., physical activity). However, for children, reducing energy intake could compromise growth or lead to possible eating disorders. In contrast, focusing on physical activity could potentially lead to a lifetime of regular physical activity (Goran et al., 1999). Indeed, as early as 1996, a report from the Surgeon General (1996) had recommended that everyone over the age of 2 years of age accumulate 30 minutes of moderate physical activity, preferably every day. In 2002, the National Association for Sport and Physical Education released daily physical activity guidelines for infants, toddlers, and preschoolers as well as older children. Seven years later (2009), these guidelines were updated (Goodway et al., 2009). Subsequently, guidelines have continued to be forwarded in other countries including ones recently from the Chief Medical Officer of the United Kingdom (2019). For those in the fields aligned with physical activity (i.e., kinesiology, physical education), the focus was to adopt strategies to raise physical activity levels in increasingly sedentary children. Not surprisingly, those in the field recognized that if the goal were to promote lifelong physical activity participation, then providing children with the opportunity to become skillful movers would be critical (Barnett et al., 2009; Stodden et al., 2008).

Thus the third approach to motor development in the 21st century, Developmental Health, captures the research that focuses on the use and promotion of motor skill development and physical activity to support and enhance health across the lifespan, and particularly in childhood. The term "developmental health" has been used, also, in psychology to capture the developmental perspective on health and well-being (Keating & Hertzman, 1999). In their book, *Developmental Health and the Wealth of Nations: Social, Biological, and Educational Dynamics,* Keating and Hertzman describe developmental health as a "full range of developmental outcomes..." (Keating & Hertzman, 1999, p. 3), which would include motor development. Indeed, the term captures well the research approach of those in the field who are focused on the relationship between children's health and their motor skill development.

This Developmental Health approach builds on a long and distinguished foundation of research in sport and exercise psychology, exercise physiology, and motor development. All recognize the importance of physical activity across the lifespan, but the challenge of engagement and adherence to daily physical activity as recommended by many distinguished groups (e.g., American Medical Association, Centers for Disease Control and Prevention, World Health Organization) remains elusive. For those in motor development, a key to meeting this challenge lies in the relationship between motor skill competence and engagement in physical activity. In the late 1970s, Harter (1978) proposed that children's motivation for participation in an activity (e.g., sport, academics) was related to their feelings of competence and their accuracy of these perceptions (Harter & Cornell, 1984). In the late 20th century, several studies used Harter's model to focus on children's perceived and actual motor competence. These studies found that children could assess their motor competence, but had a low to moderate relationship between their perception of their competence and their actual competence in children 9-11 years of age (Rudisill, Mahar, & Meaney, 1993), K-4th graders (Ulrich, 1987), and preschoolers (Robinson, Rudisill, & Goodway, 2009). Pre-schoolers who were disadvantaged and at risk for developmental delay also were poor in perceiving their actual competence level (Goodway & Rudisill, 1997).

In retrospect, this early work on actual and perceived motor competence was instrumental in the emergence of the Development Health approach. As the obesity problem among children continued to increase into the 21th century in what would be called by some, an "epidemic," the issue of children's physical inactivity moved into the spotlight. However, the early efforts had utilized, primarily, a psychosocial approach to children's physical inactivity – focusing on their motivations for being physically active and their perceptions of their motor skills, with rather less emphasis on actual motor competence. By the early 21st century, a number of motor development researchers had become interested in the problem of how to conceptualize the relationships between motor competence, physical inactivity and other mediating factors.

Stodden and his colleagues (2008) argued that what was needed to address the problem was an *interdisciplinary* and *developmental* approach to understanding the predictors of inactivity. To address this shortfall, Stodden et al. (2008) developed a conceptual model describing the relationship between physical activity and motor competence across childhood and their interrelations with perceived competence, health-related physical fitness, and weight status. Specifically, the model addressed the role of motor competence in the development of a positive spiral of engagement or negative spiral of disengagement in physical activity. That is, children with higher levels of motor competence are more likely to be physically active and demonstrate higher levels of physical fitness and perceived competence, which would reduce the risk of overweight and obesity. This, in turn, would positively influence further motor skill development and physical activity participation. In contrast, children with lower competence levels are less likely to engage in physical activity and more likely to show lower levels of physical fitness and perceived competence. This would increase the risk of overweight and obesity and negatively impact further development of motor skills and engagement in physical activity. Developmentally, the model of Stodden et al. (2008) proposed that fundamental motor skills are at the foundation of the motor competence needed for a lifetime of physical activity. These fundamental motor skills are basic gross motor skills that can be divided into in locomotor (e.g., running, galloping, skipping, hopping), object control (e.g., throwing, kicking, catching, striking), and stability skills (e.g., twisting, balancing) (Seefeldt, 1980). These fundamental motor skills form the foundation for developing context-specific skills (skills required for specific activities) and are considered necessary for successful participation in physical activities including sports, games and dance (Seefeldt, 1980). As such, motor competence during early childhood is defined, by some, as reflecting an individual's proficiency in the fundamental motor skills (Utesch & Bardid, 2019). For example, motor competence has been measured by using the Test of Gross Motor Development (Ulrich, 2019) which was developed to assess locomotor and object control skills in young children.

Potential relationships identified in the Stodden et al (2008) model have been expansively tested in the last decade. For example, the relationship between actual motor skill performance and a person's perception of these skills continues to be probed. Research has continued to show low-to-moderate positive associations between motor competence and perceived motor competence in early and middle childhood (e.g., LeGear et al., 2012; Robinson, 2011; Toftegaard-Stoeckel et al., 2010), although some studies found no significant association in early childhood (e.g., Spessato et al., 2013). It was earlier argued that perceived competence is developmental and changes over time as children grow older and their cognitive capacity improves (Harter, 1999). Stodden et al. (2008) also propose that children's ability to perceive their motor competence is a mediator variable whose accuracy becomes more established in middle childhood.

However, Robinson et al. (2015) note that is difficult to explore the association between motor competence and perceived competence in a general or domain-specific context due to a misalignment between actual and perceived competence measures. Earlier studies that perceptions of motor skills were completed using instruments that assessed motor constructs that differed between the perceived and actual measurements of motor competence. To address the need for instrument alignment, researchers have developed perceived competence assessments that more closely align with motor skills in both children (Barnett et al., 2015; Robinson & Palmer, 2017) and adolescents (McGrane et al., 2015). Recent studies that have adopted an alignment of these measures have found differences in associations depending on the skill domain. For instance, a study of Belgian and US children aged 4-5 years (Brian et al., 2018) showed that perceived competence was associated with actual competence in object control skills, but not in locomotor skills. Similar findings were found in Australian children aged 5-8 years (Liong et al., 2015).

Stronger associations are found for another part of the model since there is a growing body of literature indicating that performance in the fundamental motor skills is related to youth participation in organized and non-organized physical activity. For example, Okely and colleagues (2001) found that the fundamental motor skills of both boys and girls aged 13-15 years were significantly associated with their participation in organized physical activity – although it predicted only a small portion of that participation. A systematic review by Lubans et al. (2010) revealed positive associations between children's and adolescents' fundamental motor skill competence and their physical activity and physical fitness. More recent reviews have further supported and extended the evidence for these relationships (Barnett et al., 2016; Cattuzzo et al., 2016; Robinson et al., 2015). Furthermore, a meta-analysis reported a significant change in association between gross motor skill competence and physical fitness from early childhood to early adulthood with the relationship strengthening across age, although this paper mainly included cross-sectional data (Utesch et al., 2019). Additionally, a study by Jaakkola et al. (2019) found that physical fitness mediated the relationship between motor competence and physical activity in 11-year-old Finnish children. Khodaverdi et al. (2016) found similar results in Iranian girls aged 8-9 years for locomotor skills, but not object control skills. These findings from different countries illustrate both that the developmental health approach is global and also that contextual effects as well as gender effects can influence relationships.

A few studies have taken a longitudinal perspective to explore how early motor competence would influence later physical activity engagement and physical fitness. For instance, a longitudinal study found that object control skills during childhood predicted physical activity during adolescence (Barnett et al., 2009). Similarly, Vlahov and colleagues (2014) demonstrated that motor skill levels in early childhood (especially, object control skills) predicted physical fitness levels in adolescence. Some studies have used multilevel modeling or structural equation modeling to investigate motor competence development over time and its links with physical activity and physical fitness. For example, dos Santos et al. (2018) found that change in children's motor competence across a four-year span (from 6 to 9 years) was positively associated with change in physical fitness, but surprisingly not physical activity. As noted by the authors, the relationship between motor competence and physical activity is not straightforward and is influenced by the type of motor competence, the measures used, as well as the type and context of physical activity (dos Santos et al., 2018).

As postulated by Stodden et al. (2008), motor competence is not only linked to physical activity and physical fitness, but also to weight status. Several studies have found an inverse association between motor performance and weight status in typically developing children (e.g., D'Hondt et al., 2011, 2013; Graf et al., 2004; Lopes et al., 2012; Okely, Booth, & Chey, 2004; Southall, Okely, & Steele, 2004) as well as in children with motor impairments (Hendrix, Prins, & Dekkers, 2014; Schott et al., 2007). These associations already occur at preschool age and strengthen during primary school years (D'Hondt et al., 2011; Kakebeeke et al., 2017; Lopes et al., 2012). The evidence is less clear in adolescence and early adulthood; some studies indicated weaker correlations between motor competence and weight status in adolescents than in children (Okely et al., 2004) whilst others reported stronger correlations (Chivers et al., 2013).

Longitudinal studies in primary school years have found that motor competence negatively influences weight status across time (D'Hondt et al., 2014; Henrique et al., 2018). Conversely, weight status has been shown to have a negative influence on motor competence over time (Coppens et al., 2019; D'Hondt et al., 2014; dos Santos et al., 2018). Additionally, Rodrigues and colleagues. (2016) found that children with a more positive development in motor competence over time were less likely to become overweight or obese at the end of primary school than children with a less positive (or negative) development. As noted by dos Santos et al. (2018), weight status may then be considered both an antecedent and consequence of motor competence. More longitudinal research is needed to further explore this reciprocal relationship across developmental time (from early childhood and into adolescence and adulthood), and how changes in this relationship relate to other health outcomes including physical activity, physical fitness and perceived competence (Robinson et al., 2015).

In summary, the Developmental Health approach brings the field back to its 1960s roots and the Normative/Descriptive period (Whitall et al., this volume) in physical fitness and motor skill development to meet the challenges of physical inactivity. A relevant model for theoretically guiding this research approach has been the conceptual model proposed by Stodden and his colleagues (2008). The research questions are focused on motor competence (both perceived and actual) and their links with health outcomes such as physical activity, physical fitness and weight status. Based on the results, the ultimate impact of this research area appears to be two-fold. One focus is to design and then test methods of helping children to become more physically active with concomitant and sustainable benefits of health. Indeed, such short-term interventions to improve motor competence in disadvantaged populations have been undertaken for some time usually with positive results (e.g., Goodway & Rudisill, 1996). There have been several reviews of interventions in typically developing populations that confirm both the positive effect of relatively short or long-term interventions and the relative lack of well-controlled studies or sustained benefits accruing and producing widespread acceptance (Logan et al., 2012; Morgan et al., 2013; Lai et al., 2014). As an example, a trial in Australia aimed to determine whether the benefits from a 10-month intervention were maintained three years later (at age 8) (Zask et al., 2012). The girls in the intervention over the three years maintained their object control skill advantage in comparison to the girls in the control group. For the boys, the advantage of the intervention at three years disappeared. After three years, there were no longer intervention/control difference in the children's locomotor skills. The second focus addresses this issue by trying to impact policy or legislation on a large-scale. One of several examples of this work is being undertaken in the country of Wales where local government is providing funding to promote physical literacy in all of its schools (Wainwright et al., 2019). Physical literacy is a relatively "new" term that describes the attributes that children need to pursue physical activity across the lifespan. It is defined as …"the motivation, confidence, physical competence, knowledge, and understanding to value and take responsibility for engagement in physical activities for life" (International Physical Literacy Association, May 2014). As a replacement for the term physical education, it remains to be seen whether this term becomes universally recognized and influential for research.

Future Directions

In summary, we have described three independent, parallel research approaches to the study of motor development each emerging around the turn of the century. Our focus has been on understanding typical motor development and thus we acknowledge omitting research from the medical field as well as selecting examples that may not reflect the totality of research on motor development. In this last section, we turn to the future. In terms of quantity, quality, and significance, the future of motor development research in the 21st century is bright (Robinson, 2018). All three research approaches – Developmental Systems, Developmental Motor Neuroscience, and Developmental Health – are asking impactful questions and have generated, to date, a strong and significant corpus of work that informs the education and rehabilitation fields as well as policy and legislative action. Each is important to our understanding of motor skill development, but no level of analysis is privileged and it is unclear whether the approaches will converge or remain relatively independent. What unifies the three research approaches is the realization that understanding how and why motor skills develop is important even if the information is for different purposes. They are linked by the realization that understanding the development of all co-developing systems, the antecedents and mechanisms underlying both typical and atypical movements and the effect of environmental factors all contribute to a foundation for a healthy active lifestyle.

We would suggest for consideration some research directions that might provide impactful steps forward. Some may apply to only one approach and others, such as methodologies, may apply to all three approaches.

1. Longitudinal Designs. Development is about change over time and as such we encourage more longitudinal designs. These designs may use short time frames as in microgenetic studies, but also, when possible, employ designs over longer time periods of an individual's lifespan. Cross sectional designs and over interpretation of mean data do not provide accurate developmental trajectories upon which to base and test hypotheses. Newer statistical methods have been around for some time, such as non-linear random coefficient modeling (e.g., King et al., 2011) which characterizes trajectories of change for each individual as well as determining a population-specific model that is not the same as computing means across subjects where the mean may not correspond to any particular participant. Along the same lines, single-subject and n of 1 designs, particularly if they involve many different measures, also are a good way to improve the knowledge base about how motor skills actually develop across a time period in the lifespan.

2. Big Data. At some point, we need data from large samples from multiple data collection sites. In addition to providing statistical validity, such designs allow more research questions to be answered and, specifically, allow the influence of regional and/or international environmental contexts to be measured. There are already some examples of this in the Developmental Health approach (e.g. UK ALSPAC, Fraser et al., 2012). The addition of mixed methods where qualitative

data are collected and analyzed should also increase our understanding of the context and developmental history of participants.

3. Genetics. Gene expression has become easier to measure and could be included in future motor development work. While there is still debate about the exact role of genetic expression vs. environmental influences on motor development, there is recognition that gene expression itself is influenced by environmental factors (physical, social and cultural) in a bi-directional relationship (Gottlieb, 2007). Some researchers are beginning to explore gene variation and its effect on a range of developmental health outcomes, including motor skills. An example of the value of this type of approach is offered by a new developmental model by Schott (Schott, 2019; Schott & Klotzbier, 2018) which incorporates the joint influences of aging and life-course experience on structural and functional capabilities. In this lifespan longitudinal model, neural resources can be either enriched or depleted by protective (e.g., fitness, education) or risk factors (e.g., obesity, sedentariness), which in turn influence brain health and cognitive control processes and consequentially motor development across the lifespan.

4. Aging. As noted earlier, this area of research has expanded greatly, but could benefit from a developmental and longitudinal approach rather than the more common cross-sectional and/or matched control paradigms found in the literature. For example, following the course of motor control deterioration and motor skill compensation over decades would be a costly endeavor, but careful planning of essential measures including cognitive attributes and recording of contextual factors including activity episodes would provide a range of developmental (aging) profiles. Such efforts would be most fruitful if they involved multiple complementary research perspectives.

5. Inter-disciplinary teams. Measuring gene expression and using sophisticated statistical analytical tools as suggested above requires inter-disciplinary teams. These teams also might

include, for example, exercise physiologists, developmental/education psychologists, sport/exercise psychologists, biomechanists, neuroscientists, gerontologists all of whom are interested in motor behavior and, often, its development. One area of research that already is an integral part of the Developmental Systems approach is developing across the other two research approaches and involves investigating the relationship and effect of motor skills and physical activity on developmental factors in children like emotional regulation, executive function, and attention (cf., Cairney et al., 2019; Tomporowski & Pesce, 2019). Indeed, the work of Pesce is an excellent example of work that fits into both the Developmental Systems approach (Pesce et al., 2016) as well as the Developmental Health approach (Alvarez-Beuno et al., 2017). In addition, Pesce and her colleagues have argued for the interplay between motor creativity and creative thinking and this is certainly one way forward that might include interdisciplinary teams (Scibinetti et al., 2011).

6. Assessment: To date, several motor assessment instruments have dominated the research studies in the late 20th and 21st centuries. But while these instruments have appropriate psychometric properties (e.g., validity, reliability), they generally are limited in age range (e.g., infancy, preschool, ages 3-11 years, 3-16 years, 4-21 years) and limited in range of motor skills (e.g., gross motor skills, fine motor skills) and underlying processes (e.g., upper-interlimb coordination, dexterity, postural control) assessed. If we are to understand the development of motor skills across the lifespan, then we need to identify the important constructs and the test items that will provide us with a lifespan assessment of motor skill development for those typically and atypically developing.

In sum, we do not have a crystal ball to predict the future and it would be a sign of hubris to think that we can predict the most important motor development questions for even the next ten years. What we will say is that we hope the future will lead to questions and collaborations between the three research approaches we have outlined in this paper. With an eye on enhancing and securing the future of research among and within the three parallel motor development research foci, the International Motor Development Research Consortium was formed in 2015 with the mission of fostering research collaborations around the globe.

Clearly, there is much work to do in the future of motor development, but over two centuries, beginning with the baby biographers in the 1800s, we have developed remarkably as a field. As we go into the future, it is clear. We have much to offer in solving contemporary problems associated with motor behavior and its development. So as Robinson wrote in 2018, motor development is "…a field with a bright future."

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