The Pennsylvania State University

The Graduate School

College of Health and Human Development

THE EMERGENCE AND DEVELOPMENT OF REACHING IN INFANCY

A Dissertation in

Kinesiology

by

Mei-Hua Lee

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

May 2011

The dissertation of Mei-Hua Lee was reviewed and approved by the following:

Karl M. Newell
Professor of Kinesiology
Head of the Department of Kinesiology
Dissertation Adviser
Chair of Committee

John Challis
Professor of Kinesiology

Rick Gilmore
Associate Professor of Psychology

Cynthia Bartok
Assistant Professor of Kinesiology

*Signatures are on file in the Graduate School

ABSTRACT

The development of reaching movements is influenced by the interactions among the organism, task, and environmental constraints (Kawai, Savelsbergh, & Wimmers, 1999; Pick & Carman, 1994; Newell, 1986; Thelen; 1981). This dissertation addresses the general issue of the development in infancy of goal-directed arm movements under the influence of different sources of informational constraints. More specifically, the main focus was to investigate the role of environmental constraints including object properties, visual and audition feedback of the arm trajectory on the development of prehension during infancy.

In Experiment 1, it was found that as infant age increased (10 – 14 weeks) through the phases of object-oriented movements, the distinguishing feature was that there was a decrease in movement jerk (when normalized to a dimensionless quantity), which reflects the increasing ability to adaptively modulate arm movements. This change in the dynamic characteristics of the object-oriented arm movements precedes the onset of goal-directed reaching movements and is hypothesised to reflect a critical variable in the infant developmental process of learning to reach in prehension.

In Experiment 2, the influence of auditory feedback on the development of reaching movements in infancy was investigated at 10-14 weeks of age. The results showed that before the onset of reaching, the amplitude of the arm movement increased when the auditory feedback was provided. Also, at the point of reaching onset, the number of reaches increased when the auditory feedback was presented. Together, these results showed that before the onset of reaching, infants are able to use auditory feedback to explore the possibilities for action, and that subsequently the primitive form of these

object-oriented arm movements is developed into more skilled and goal-directed reaching movements.

In Experiment 3, we addressed the question of whether the development of prehension was influenced by the visual information of the hand trajectory and object properties at reach onset, 6 mo and 1 yr of age. It was found that age of onset of reaching for an object was earlier when the visual feedback of the hand trajectory was available. However, the effect of the visual feedback of the hand trajectory diminished after reach onset; there were no significant difference in terms of movement speed and smoothness at 6 mo and 1 yr of age. Infants also reached for the larger object earlier and with higher velocity than for the smaller object. Collectively, these results reveal the distinct roles of visual information of the hand trajectory and object property on the development of prehension during the infancy.

In sum, the results of the experiments highlight the importance of exploratory behavior in early infancy and how exploratory behavior prior to the onset of reaching movements can be channeled through the vision and auditory information feedback. These findings are consistent with the perspective that the development of motor skill is influenced by the interactions among the organism, task and environment constraints. The weightings of the constraints as boundary conditions change at a certain developmental time in the emergence and mastering of the movement patterns.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

First, I am heartily thankful to my supervisor, Dr. Karl Newell, whose expertise, along with his ceaseless encouragement and support, has been essential in making this journey possible and enjoyable. In countless email conversations, he has offered to help in every way he possibly can.   And seeing him do "the signature dance" is always a delight. I would also like to thank the members of my committee, Drs. John Challis, Rick Gilmore, and Cynthia Bartok, for their consistent guidance and encouragement over the past several years. It was a true pleasure to have all of you as part of my dissertation process.

My gratitude is also extended to Tim Benner for his help with technical issues, to Dori Sunday who has been there from the very beginning, and to Brenda Wert who always cheerfully offered to help. Special thanks also goes to my dear friends, Rajiv Rangnathan, Adam King, Kimberlee Jordan, Aileen Costigan, Xiaogang Hu, Wang Zheng, Tsung-Yu Hsieh, and all of the members of the Motor Behavior Lab. This journey would not been such fun without you, and I treasure every step we took together. I know our friendship will last forever.

Last but not least, this dissertation is dedicated to my parents, brother, and sister, for their support throughout the years. Their endless support has let me pursue my dream, and for that I am truly grateful.

CHAPTER 1. INTRODUCTION

The development of prehension throughout the first year of life shows significant changes in the qualitative and quantitative properties of the fundamental movement patterns (Gesell, 1929; McGraw, 1943; Shirley, 1931). However, the sequence of change in the movement patterns is not universally invariant across infants although there is considerable order and regularity to their emergence. In other words, not all babies show the onset of reaching or grasping at the same biological or chronological age. This is because the development of prehension is influenced by the interaction of the organism, task and environmental constraints (Newell, 1986; Savelsbergh, Van Hof, Caljouw, Ledebt, & Van der Kamp, 2006).

Prehension is an act that is primarily composed of reaching and grasping movements. Typically, reaching is the positioning of the arm and hand near the object, while grasping involves actions on the hand and fingers, and has the function of object manipulation (Bower, 1972). Before there is voluntary movement of the arm and hand in reaching and grasping, there are crude voluntary oscillatory shoulder and elbow movements. This type of infant behavior has been categorized as spontaneous arm movements (Prechtl, 1990; Thelen, 1979).

There are different views of the function of spontaneous movements: 1) as a developmental phenomenon - Prechtl (1990) found that qualitative changes of spontaneous movements may be a marker of neurological dysfunction; 2) as a compensatory self-stimulatory movement (Thelen, 1980, 1981); and 3) as a primate form for more advanced goal-directed movements - for example, the development of prehension can be viewed as a progress of learning to control and sculpt undirected, spontaneous movements into controlled, goal-directed movements (Turvey & Fitzpatrick, 1993). Furthermore, it has been shown that spontaneous movements have a voluntary component as in their adaptive variation to different eliciting contexts (alertness, social interaction, object presented, posture changes, feeding etc.) (Thelen; 1981; Piek & Carman, 1994; Kawai et al., 1999). Indeed, the relevance of the spontaneous behavior that ensures the infant perceiving the underlying “causal texture” of the events going on and the infant’s own relation to them is remarkable (E. J. Gibson, 1991).

In considering grasping, the grip configurations can be divided into two functional categories of precision and power grips (Napier, 1980). The sequence from power to precision grasping in infants has been proposed from the maturational viewpoint of development (Halverson, 1931). This viewpoint, however, has been challenged by dynamical systems perspectives and some related experimental findings. Indeed, several studies have shown that infant grip configurations are influenced by the properties of the objects they are reaching for (shape, size and texture) (Lee, Liu, & Newell, 2006; Newell, McDonald, & Baillargeon, 1993; Newell, Scully, McDonald, & Baillargeon, 1989; Newell, Scully, Tenenbaum, & Hardiman, 1989; Siddiqui, 1995). Thus, object properties play an important role of mediating the emergence of infant grip configurations in prehension. In the dynamical systems framework, the patterns of grip configuration are emergent properties of the constraints imposed on action rather than products of prescriptions for actions (Kugler, Kelso, & Turvey, 1982).

Infancy is a period of rapid development but babies’ perceptions are not still fully mature. In the ecological psychology perspective, perception and action mutually constrain each other (Gibson, 1979). Therefore, how infants perceive information through the five major sensory channels (vision, hearing, touch, taste, and smell) is a crucial topic for the better understanding infant motor development. More specifically, what information infants can perceive in the early development of prehension, and how infants gain the control of movement in relation to the task and environmental constraints still needs further investigation. In this sense, the study of the interaction between visual control and prehension in infancy opens a window to understanding the development of movement coordination.

In brief, this dissertation addresses the general issue of the changes of spontaneous arm movements to goal-directed reaching coordination patterns under the influence of different sources of constraints. More specifically, the main focus is to investigate the role of informational constraints on the development of prehension during infancy by manipulating vision feedback of the arm trajectory, object properties, and auditory feedback. It is hypothesized that the developmental course of infant hand movement in prehension is modulated dynamically within the constraints of actions.

Focus of the Dissertation

The emergence of prehensile skills in infancy is one of the central issues in motor development. The change in infancy from spontaneous arm movements to goal-directed reaching movements has received limited investigation particularly in considering the individual characteristics of the developmental pathway of change in behavior over time. In the dynamical systems perspective, the new skill is influenced by the interplay of infants' existing anatomical or dynamic properties and the preexisting movement dynamics to the new task demands (Thelen, 1994; Thelen, Corbetta, & Spencer, 1996). More importantly, how infants discover the relevant information in order to make a functional match between what the environment affords and the task demands will be addressed in this dissertation. The primary objective of this dissertation is to investigate the transition of infant prehensile spontaneous movements to goal-directed reaching coordination patterns as a function of particular constraints in action.

In Experiment 1, we examined the characteristics of arm movement that precede the onset of goal-directed reaching movement. The purpose of this study was to quantitatively describe the changes in the qualitative properties of limb movement that precede the transition from early prehensile movements to goal-directed reaching. The qualitative and quantitative properties of arm movements at three phases of development – (a) early object-oriented arm movements (10-12 weeks), (b) late object-oriented arm movements (12-14 weeks), and (c) non-reaching movements at the onset of reaching (14-16 weeks) were analyzed.

In Experiment 2, we investigated the issue of whether changes in infants' spontaneous arm movements systematically map to the changes in the environment. More specifically, we were interested how augmented information may channel the development of reaching movements in infancy. Auditory concurrent feedback of hand movements was provided to investigate whether concurrent auditory feedback can influence the development of reaching in infancy.

Experiment 3 was a longitudinal study of infant prehension that allowed the investigation of the transition from spontaneous movements to goal-directed movements in infancy as a function of visual information feedback of the hand trajectory and object property. The development trajectory from reach onset to 6 months, and 1 year of age was analyzed.

Together, the experiments were setup to provide additional information on the developmental course of infant hand movement in prehension under the influences of different sources of constraints. More specifically, the central theme of this dissertation investigates the characteristics of the spontaneous arm movements that precede reaching. Further, can the pattern of spontaneous arm movements and reaching movements be channeled by the influence of environment constraints (visual feedback of the arm trajectory and auditory feedback) and what is the developmental trajectory of the prehension under the influence of these constraints.

CHAPTER 2. LITERATURE REVIEW

Perspectives on infant motor development

The majority of studies on infant motor development have focused on phylogenetic movements such as reflexes, kicking, crawling, reaching and walking (Thelen et al., 1993; Adolph & Berger, 2006; von Hofsten, 1991, 1993). Here we use the example of the study of the stepping reflex to illustrate the insight of different theoretical perspectives on infant motor development. A stepping reflex can be produced when a baby is held upright and the sole of the foot is touching a solid surface. This kind of movement is observed in the typical development of the infant from birth to 2-3 months of age. How the stepping reflex develops into an adaptive walking movement has been studied from a number of theoretical points of view.

Traditionally, the development of motor patterns has been considered from the genetic perspective of the unfolding maturation of the developing central nervous system. In this view, the decline of the stepping reflex is because of the onset of cortical inhibitory influences (McGraw, 1940). In the developmental progression of the higher cortical centers, it is established that inhibitory influences precede excitatory influences, thus suppressing the primary behavior that in this case is the stepping reflex (Humphrey, 1969).

This long standing maturational perspective of the suppression of the stepping reflex was challenged by the environmental learning perspective of Zelazo (1972a, b), who disputed that inhibition influences the practice of the stepping reflex. Further, he claimed that the reflexive substrate is converted into an instrumental activity of walking.

This view point helped shift the focus of infant motor development from the maturational development of the organism to the role of external factors of the environment. More generally, this challenge reflects the long standing debate of nature vs. nurture that still influences the study of development in many fields (Thelen, 1995).

There are other experiments that illustrate the importance of the impact of "training" in infant motor development. Lagerspetz, Nygard, and Strandvik (1971) trained infants to crawl for 15 mins daily over 3 weeks. The training group revealed advanced crawling movements earlier than controls (who received no training). The effect of exercise has also been evidenced in cross-cultural observations, in which infants were shown to be advanced in the movements in which they had been exercised like sitting, standing and walking (Super, 1976).

In the dynamical systems perspective, the development of the patterns of coordination in infancy is a consequence of emergent properties of the principles of self organizing systems rather than expression of genetic or environmentally acquired prescriptions for action (Kugler et al., 1982; Kugler, 1986; Thelen, Kelso, & Fogel, 1987; Thelen & Smith, 1994). More specifically, this approach investigates the sources of constraint to action and their influence on the movement dynamics of behavioral development (Newell, 1986).

A seminal study by Thelen and Fisher (1983) elegantly demonstrated that an infant's stepping reflex can reappear when the infant's lower body is immersed in water because the effect of gravity on limb movement is sufficiently mediated under this condition. This study also supports the idea that muscle strength may limit behavioral expression at times of rapid physical growth and in the situations where strength is taxed

(Thelen & Fisher, 1983; Thelen, Fisher, Ridley-Johnson, & Griffin, 1982). This experiment provided evidence that the re-emergence of the stepping reflex was a reflection of the constraints rather than the emergence of a maturational prescription.

In dynamical systems perspectives, action patterns are emergent features of the confluence of constraints imposed on the organism, environment and task interaction, rather than prescriptions for action as is typically postulated by the maturation hypothesis and the extant cognitive formulations of motor development (Kugler et al., 1982; Newell, 1986). The constraints on the action provide boundary conditions as a principle for organizing the coordination (Newell, 1986, 1996). In other words, within the boundary conditions there are many possibilities of potential actions, the emergence of the action act upon the interaction from organism, task and environment constraints.

In dynamical systems view, there is no a priori factor that predetermines the emergence of movement patterns. On the other hand, the solution of the movement patterns is a function that has different weightings on the each component at a particular age. This function is composed by components of the organism, task and environment constraints. There are some important properties of this function: 1) the interaction among components is not predetermined in advance; 2) the ratio of the weighting in each component is not fixed; and 3) changes in the function may be realized by the critical value changes in the weighting of a component at a particular time (Kugler et al., 1982).

Spontaneous arm movements

Studies of the development of prehension have focused on the sequence of the emergence of the components of prehension, that is, from reaching, to power grips, to precision grips (Napier, 1956). The classic study of Halverson (1931) used a one-inch cube as the object and moved it distally and proximally with respect to the infant's palm. This study provided a detailed record of infant prehension and the general development sequences of prehension. Recent studies have shifted the focus of the developmental sequences of prehension to the arm movements that precedes onset of reach (Bhat & Galloway, 2006 ; Lee, Bhat, Scholz, & Galloway, 2008; Thelen, 1979; 1981, Piek & Carman, 1994; von Hosten, 1982; von Hofsten & Rönnqvist, 1993).

Before onset of the goal-directed movements in infancy, there are rhythmical movements that are seemingly unorganized behaviors that can be observed during first year of life or so on. These types of movements are produced by the parts of the body or whole body and have the characteristic of repeated or rhythmical components, the form could be kicking, arm waving, banging, rocking and swaying. Wolff (1967) observed the spontaneous movements in infants with Down's syndrome, and found the sequence of spontaneous movements is paralleled to the progression of motor development. He claimed that function of spontaneous movements is not "sufficient but necessary" substrate for more advanced movements (Wolff, 1967, 1968). In addition to this, Thelen's (1979) dissertation investigated the pattern of spontaneous movements of 20 infants over a year period and found that the mean age of spontaneous movement onset and infant's average Bayley motor score was highly correlated. Also, the frequency of the spontaneous movements was influenced by the social interaction with caregiver, object presented, and feeding conditions. Later, Thelen (1981) proposed that the function of these rhythmical movements is the transition behavior between unstructured movements to more advanced goal-directed movements, that is, those spontaneous movements were coincident with emergent voluntary movements. For example, arm waving coincided with emergent reaching; arm banging precedes object manipulation skill (Thelen, 1979).

These observations support the view that infants actively produce spontaneous movements, and that these are accompanied by concomitant visual, proprioceptive, haptic and vestibular consequences. As they develop the movement skill, with further differentiation and integration of the perceptual information, the process of the action perception loop continues as they develop (Thelen, 1981; E.J Gibson, 1988).

Vision and prehension

Vision mediates the development of prehension in many different ways (Gibson, 1979; Bower, 1972). The development of reaching behavior can be divided into visually triggered and visually guided based on the time course of the hand movements (Clifton, Muir, Ashmead, & Clarkson, 1993; Clifton, Rochat, Robin, & Berthier, 1994; Piaget, 1952; Laskey, 1977). In the early stages of reaching behavior, it has been hypothesized that the reach is visually triggered, that is, the visual location of the target is used to initiate the movement. Thus, the position of the object is perceived visually, while the position of the arm is perceived proprioceptively. On the other hand, the last part of the reach where the hand approaches and contacts the object is considered visually guided. In this case, the position of the arm is perceived visually with reference to the target, allowing precise adjustments to be made to ensure the accuracy of the reach (Jones & Lederman, 2006).

This interpretation is similar to that used in the classic study on the visual control of the kitten (Hein & Held, 1967) where visually triggered was defined as lowering the kitten toward a continuous surface (no accuracy is required). In contrast, the visually guided was defined as lowering the kitten toward a discontinuous surface, in which the visually guided placing to hit the prong was required (accuracy is required). When it was manipulated whether the kitten can see their own limb or not, the results showed that visually triggered paw extension develops without sight, but visually guided paw placing requires prolonged viewing of the limbs. These results further show that the sight of the limb has an impact on the accuracy of the final reaching movement but not for the reaching initiation.

In contrast, studies have shown that infants at an age as early 3 to 5 days old are able to control their hand movements with the vision of their own hand movements. These results indicate that neonates have some control of their own spontaneous movement even at early age when the vision feedback of the arm was available (van der Meer, van der Weel, & Lee, 1995). Also, Gesell and Ames (1947) used cinema-analysis observing infants from 16 through 60 weeks of age and revealed that behavior changes in infancy when a mirror was presented in front of the infant. The infants moved their arm more actively when the mirror was present. Indeed, in this mixed-cross sectional and longitudinal design, it was shown that the hand and arm movements do not change in a monotonic fashion; instead, there is a discontinuous progression and regression of activity level of the hand and arm movements.

Thus, there are two primary and contrasting views as to the role of visually guided reaching in infancy. One viewpoint is that reaching is planned before it is executed so that, for example, visual guidance of the hand is not necessary to achieve object contact (Clifton et al., 1993). A second viewpoint is that infants need the online vision of their hand to reach and contact the object (Piaget, 1952; Clifton, Perris, & Bullinger, 1991). There is evidence for both points of view.

Several studies have shown that infants do not need to see their hand to reach and contact an object (Clifton et al., 1993; Clifton et al., 1994). In a longitudinal study, Clifton et al. (1993) recorded the emergence of reaching for objects by 6-to 25-week-old infants in three different conditions, natural light, when the object was glowing against a dark background, or glowing with auditory cues in complete darkness. The results showed that the onset time of infants' first contact with the object was at about the same age in all conditions (mean age of light, 12.3 weeks, and for dark, 11.9 weeks). In another study, the reaching trajectory in 6-month-old infants showed a similar movement speed profile to the hand trajectory regardless of the presence or absence of vision of the hand (Clifton et al., 1994).

In contrast to these results, and as mentioned above, 3 to 5 day-old babies are able to control their hand movements when vision of the hand is available (van der Meer et al., 1995). Also, Laskey (1977) occluded sight of body and hand by an apparatus and found that 5 1/2 to 6 1/2 month-old infants' reaching was compromised without the sight of their hand movement, but that the prehension of 4 1/2-month-olds infants was less affected. Taken together, these findings imply that there are age-related discontinuities in the use of visually guided reaching in infancy.

It appears that visual guidance facilitates reaching in newborns, but does not affect the onset time of reaching in infants until about 12 weeks old, and then at 5 1/2 to 6

1/2 months, where visually guided movement once again enhances the reaching behavior. However, without a systematic experimental investigation of this potential discontinuous developmental trend it is premature to draw this conclusion. Therefore, one question investigated in this dissertation was to examine in a longitudinal study the time course of the impact of visual feedback of the hand on the transition of spontaneous movement to goal-directed reaching movements and, more generally, the development of prehension in infancy. If the visual feedback modulates the development of prehension behavior then providing or enhancing the feedback at critical time points in development may facilitate prehension behavior (Bushnell, 1985).

Influence of constraints on prehension

Environmental constraints and prehension

Environmental constraints like gravity are relatively persistent and there have been some manipulations of sources of these constraints in motor development. For example, holding a baby in water or changing the position of the baby's posture to determine how gravity may affect the development of prehension movements. The results of these studies revealed that infants showed more active spontaneous movements when the body was out of rather than in water (Kawai et al., 1999). Furthermore, a seated position resulted in more reaching movements than in a supine position (Savelsbergh & Van der Kamp, 1994).

On the other hand, in prehension the objects to be picked up have physical properties like size, weight, and texture. In infant reaching and grasping, several studies have shown that infant grip configurations are also influenced by properties of the objects they are reaching for (shape, size and texture) (Lee et al., 2006; Newell et al., 1993; Newell et al., 1989; Siddiqui, 1995). These findings highlight the importance of the object properties mediating the development of the infant movements, that is, the pattern of grip configurations (using a precision grip, power grip, or adding the other hand to form a two hand grip) mapped to the object properties.

In addition, the findings of these studies also illustrate the interactive effect of developmental age and the constraint of objects properties. For example, younger infants have shown a higher frequency of touching solid objects and grasping for soft objects, whereas older infants readily grasped both soft and solid objects. More specifically, the interactive influences of age and environmental constraints on grip configurations are more strongly mediated by the body and object scale not by the chronological age. In children aged 6-12 years, the transitions of the grip configurations have been modeled using a body and object scaled equation (Cesari & Newell, 2000a, 2000b). These studies showed that infant grip configurations were organized by the interaction of body/object scale and the goal of the action. Object properties will be manipulated in this study of infant prehension.

Task constraints and prehension

Task constraints are related to the goal of the action or the rules that specify the action (Newell, 1986). Task constraints do not have to be a physical substance; these could be instructions, directions, or rules. For example, follow the rules; we will not dribble a football or kick a volleyball in the game. This is real example of how the rules and regulations can mediate the coordination pattern of movements. On the other hand, in the study of infant behavior, we can not verbally instruct infants to follow rules. Instead, we can only setup the experimental conditions that elicit them to perform behaviors that we are interested in. For example, in a study of infant mouthing and grasping behavior, the main findings support the idea that infants modify their grip configurations depending on the goal of the action according to whether they mouth objects or perform other grasping actions (Whyte, McDonald, Baillargeon, & Newell, 1994).

Organism constraints and prehension

The proportions of human form change significantly from fetal to adult age (Brandt, 1980; Visser, 1966). The relative changes between birth and the second year are more pronounced than those, for example, between the thirtieth and fortieth year. During the fetal period, the development of dorsal head region has more rapid changes than in the ventral parts. Typically, the head region is relatively large and is about half of the size of the total body when a fetus is about 2-month-old. In newborns, the head proportion to the body size is about 1:4 ratio whereas in adult is about 1:8 (Robbins, Brody, Hogan, Jackson, & Greene, 1928; Shuttleworth, 1949). This disproportion between the upper-body and lower-body has a significant influence on the development of upright posture in infant development and the postural support for reaching.

Despite the changes in the skeleton, the changes in the body composition also play an important role of mediating the changes in the movement patterns of the developing system. In the development of walking, it has been shown that muscle strength may constrain behavioral expression in newborn infants (Thelen, Fisher, &

Ridley-Johnson, 1984). In the development of infant prehension, reaching movements are only established when the posture control is obtained. In fact, the organization of muscle activation is very distinct for spontaneous and goal-directed arm movements. During the spontaneous movement, there are large intra- and inter-individual variations in the muscle activation (muscles related to the posture control, i.e. neck and trunk). In contrast, during reaching movements, the muscle recruitment tends to follow top-down trend from neck to trunk (van der Fits, Klip, Eykern, & Hadders-Algra, 1999).

In summary, this dissertation addresses issues on the changes in the spontaneous arm movements that precede reaching movement. Based on the concept of task, organismic, and environmental constraints on the development of motor skill, we further investigate the role of informational constraints on the development of prehension during infancy by manipulating vision and auditory feedback of the arm trajectory and object properties. Thus, the overall aim of this dissertation was to further the understanding of the influence of the informational constraints on the development of prehension.

CHAPTER 3: CHANGES IN OBJECT-ORIENTED ARM MOVEMENTS THAT PRECEDE THE TRANSITION TO GOAL-DIRECTED REACHING IN INFANCY

Abstract

The emergence of prehensile skills in infancy is one of the central issues in motor development. The objective of this longitudinal study was to quantitatively describe the changes in the object-oriented arm movements that precede the transition to goal-directed reaching movements in infancy. Arm kinematics in ten full-term infants were recorded biweekly from the age of 10 weeks to 28 weeks while objects were presented for prehension. The kinematics were analyzed across three progressive phases of object-oriented arm movements (early, before and after onset of reaching movements). As infant age increased through the stage of object-oriented movements, the distinguishing feature was that there was a decrease in movement jerk (when normalized to a dimensionless quantity), which reflects the increasing ability to adaptively modulate arm movements. This change in the dynamic characteristics of the object-oriented arm movements precedes the onset of goal-directed reaching movements and is hypothesised to reflect a critical variable in the infant developmental process of learning to reach in prehension.

Introduction

A fundamental question for understanding motor development is how a system composed of many “degrees of freedom” (Bernstein, 1967) realizes adaptive coordinated movement with precise spatial and temporal patterning (Thelen, 1989). This issue is particularly relevant for the study of motor development. However, typical analyses of infant motor development describe only qualitative changes in motor performance through a frequency count of the onset and prevalence of a given sequence. This is in part because it is a challenge to determine a single variable that describes the changes in the fundamental infant coordination patterns. The essence of this problem was captured by McGraw and Breeze (1941) as “during development, the behaviors are constantly changing, changing in form and changing in magnitude; there are no common units, such as pounds or inches, for the representation of behavior” (p.267).

The development of prehension throughout the first year of life shows significant changes in the qualitative and quantitative properties of movement patterns (Gesell, 1929; McGraw, 1943; Shirley, 1931). Prehension is the action category characterized by reaching and grasping movements. Reaching involves positioning of the arm and hand near the object, while grasping involves actions of the hand and fingers that are used to manipulate the object (Bower, 1972). However, even though there is considerable order and regularity to the emergence of the fundamental movement patterns, the sequence of change in prehension movement patterns is not universally invariant across infants. This is because the development of prehension is influenced by the interaction of the organism, task and environmental constraints (Lee, Liu, & Newell, 2006; Newell, 1986; Savelsbergh et al., 2006).

In terms of the regularity observed, qualitative analyses have revealed characteristic features of arm movements during the development of prehension (von Hofsten & Ronnqvist, 1993). In particular, there is a period before the onset of goal-directed reaching that is characterized by oscillatory shoulder and elbow movements. This type of infant behavior has been categorized as spontaneous arm movements (Prechtl, 1990; Thelen, 1979). Even though these movements appear to be undirected, several studies provide evidence that these arm movements observed prior to reaching are not random. Using four-dimensional (4D) ultrasonography, Myowa-Yamakoshi and Takeshita (2006) found that close to half of the arm movements they observed in utero resulted in the hand touching the mouth. The functionality of these movements can be inferred from the fact that fetuses opened their mouths before their hands came in contact with their mouths. Further, fetal reaching movements have also been shown to become more direct and straight towards the target (i.e. the eye and the mouth) by 22 weeks of gestational age (Zoia et al., 2007). In the case of neonates, early arm movements have been shown to have directional structure (von Hosten, 1982; von Hofsten & Rönnqvist, 1993), again indicating that they might be functional and not random.

There are different views of the function of spontaneous movements in infancy. They have been interpreted as: a) a developmental phenomenon - Prechtl (1990) found that qualitative changes in spontaneous movements may be an indicator of neurological dysfunction; b) a compensatory self-stimulatory movement (Thelen, 1980, 1981); and c) a primitive form for more advanced goal-directed movements - for example, the development of prehension can be viewed as the progression of learning to control and sculpt undirected, spontaneous movements into controlled, goal-directed movements (Turvey & Fitzpatrick, 1993).

When considering the functionality of spontaneous movements as a means to explore the possibilities for action, E.J. Gibson (1997) proposed that the process of learning includes three principles: spontaneous exploratory activity, observation of the consequences of exploratory activity, and selection of one variable as a means of exploration. Spontaneous movements have been shown to have a voluntary component, as observed when infants adapt these movements to different eliciting contexts – alertness, social interaction, the characteristics of the object presented, posture changes, and feeding (Kawai et al., 1999; Piek & Carman, 1994; Thelen; 1981). Furthermore, according to E.J Gibson (1988), the relevance of the spontaneous behavior ensures the infant perceives the underlying "causal texture" of the events going on and the infant's own relation to them.

Thelen et al. (1993) provided detailed descriptive profiles of how infants modulate their *intrinsic dynamics* during development to transition from spontaneous arm movements to goal-directed reaching movements (Turvey & Fitzpatrick, 1993). The meaning of intrinsic here is not equivalent to innate or genetic, rather, it refers to the properties of effector systems that are channeled by the infants' existing anatomical or movement dynamics in the absence of any specific task goals. Thelen et al. (1993) concluded that movement speed was the relevant kinematic variable that not only explained the energetic level of the infant, but also captured the organization of the hand path trajectory (Thelen et al., 1996). In other words, Thelen et al. (1993) suggested that a measurement of movement speed reveals quantitative changes in an aspect of prehensile coordination patterns. However, the kinematic variable of average movement speed does not provide a sufficient description of *how* the infant moves and could therefore be insensitive to subtle changes in the movement patterns.

The objective of the present study was to quantitatively describe the changes in the qualitative properties of limb movement that precede the transition from early prehensile movements to goal-directed reaching. In the context of the current experiment, we use the term “object-oriented” movements to indicate movements made by the infant in the presence of an object (or toy) presented by the experimenter, where the arm did not come in contact with the object. Arm movements that made contact with the object were termed “reaching movements”, and the term “non-reaching movements” was used to denote object-oriented arm movements that occur in the same session where the infant first made reaching movements (Thelen et al., 1993).

To quantify these changes, we calculated several kinematic variables of limb movement including jerk to measure the structure of the change of infant prehensile movement patterns as a function of infant developmental age (early, prior to and after the onset of reaching movements). Jerk is the rate of change of acceleration (or the third time derivative of displacement), and has been used to measure the smoothness of skilled and coordinated movements (Hogan, 1984; Hogan & Flash, 1987). Jerk has been used to compare the smoothness of the movement between stoke patients and control participants (Platz, Denzler, Kaden, & Mauritz, 1994; Rohrer et al., 2002), the progression of motor dysfunction in Huntington’s patients (Smith, Brandt, & Shadmehr, 2000), and to quantify the development of reaching movements in infancy (Berthier & Keen, 2006; Berthier & Carrico, 2010).

In the current study, the variable of dimensionless jerk was used to quantify the changes in the dynamic characteristics of object-oriented arm movements and their relation to the onset of reaching. Given that object-oriented arm movements are mutiplanar movements (along the body's longitudinal axis, abduction and adduction, accompanied by shoulder flexion) with varying timing and amplitude (von Hofsten & Ronnqvist, 1993), the characteristics of the object-oriented arm movements can be better captured by dimensionless jerk. The term "dimensionless" is used to indicate that the jerk is normalized by appropriate quantities (such as movement time, speed, or amplitude) so that the jerk measure becomes unitless. This process of making the jerk dimensionless has the advantage of capturing the shape of the speed profile while being relatively uninfluenced by the absolute changes of movement amplitude or time (Hogan & Sternad, 2009).

We examined the characteristics of arm movements at three phases of development – (a) early object-oriented arm movements (10-12 weeks), (b) late object-oriented arm movements (12-14 weeks), and (c) non-reaching movements at the onset of reaching (14-16 weeks). In all these phases, only the trials without contact of object were analyzed (See Methods for details). It was hypothesized that as infants gained more control of their arm movements, the smoothness of movement would increase, leading to a decrease in jerk from early object-oriented arm movements to the late object-oriented arm movements. However, since these changes reflect a reorganization of movements in order to perform the task of reaching, we predicted that these changes would diminish after reaching movements were developed.

Methods

Participants

Ten healthy full-term (37 to 42 weeks gestational age) infants (5 female) participated in the experiment. Each infant started the first testing session at 10 weeks of age, was tested subsequently at two-week intervals until 28 weeks of age, and then a final test was run when the infant was 1 year old. Given the focus of the current study on the transition from object-oriented arm movements to goal-directed reaching movements, only the data from 10 weeks of age to reach onset were analyzed. Informed parental consent was approved by The Pennsylvania State University Human Subjects Review Board.

Apparatus

The infants were seated in an infant chair at a 30° recline from vertical; a seat belt held them in a stable seated posture but allowed them to move their arms and legs freely. Data were collected using a 4-camera (Sampling rate = 240 Hz) motion analysis system (Qualisys Motion Capture Systems, Gothenburg, Sweden) and two video recorders (Sampling rate = 60 Hz). For the motion analysis system, two cameras were positioned on the right of the infant and two cameras on the left. The average measurement error for this calibrated volume was < 0.5 mm For the video system, one video recorder was strutted by a tripod hanging above the chair to capture prehensile behavior on the transverse plane (i.e., a top-down view); the other one was used to capture eye movements. The motion analysis and the video camera systems were synchronized with an external LED that was triggered by the motion analysis system.

Procedure

Prior to the start of the experiment, joint markers were attached to both sides of the participant's body. These markers (10 mm in diameter) were made from black felt and were attached to the infants' wrists, forearms, and upper arms via hypoallergenic tape. Three objects were used in the experiment - a pacifier (size 2 for newborns) and cubes in two sizes (2.54 and 6.5 cm in diameter). These were presented to the infants on the open palm of the experimenter, at the midline and within reaching distance of the infants. Each object was used twice, one at a time in a random order. Each trial lasted for 30s or until the infant grasped the object.

Data Analysis

Qualitative analysis of movement category

We identified the three phases of arm movements (early object-oriented, late object-oriented and non-reaching) for each infant based on when the infant started to reach. Reach onset was defined as the first week in which the infant made contact with the presented object (Berthier & Keen, 2006; Carrico & Berthier, 2008; Thelen et al., 1993). Non-reaching movements were arm movements that occurred in the session when the onset of reaching was identified, but that made no contact with object. Once the reach onset was determined, the early object-oriented movements were defined at 4 weeks (i.e., 2 sessions) prior to reach onset, whereas late object-oriented movements were defined at 2 weeks (i.e., 1 session) prior to reach onset. The participant's object-oriented arm movements were divided into four categories: (1) no movement, where the participant did not move his/her arm; (2) little movement, where the participant moved his/her arm with small range of motion (only lower arm movements); (3) big movements, where the participant moved his/her arm with big range of motion (both lower and upper arm movements) but did not cross midline toward to the presented object; and (4) cross midline movement, where the participant moved his/her arm with big range of motion and also across the midline toward to the presented object. These movements were coded independently by two raters who each classified all the trials.

Kinematic analysis

The data selected for kinematic analysis of the object-oriented arm movements and non-reaching movements were selected using the following criteria: 1) from the 30 s observation period, we selected a duration of 15s when there was the most active hand movements (which was identified from the 2D camera and the speed profile from motion analysis); 2) the infants were looking at the object and/or noticed it before reaching (Corbetta & Thelen, 1995), and 3) the arm selected for analysis was the one that contacted the object first during the reach onset session. In other words, if the infant reached for the object with the right hand during the reach onset, then the object-oriented arm movements of the right arm were analyzed in all sessions. We also did not include trials in which the infant was not moving (based on the qualitative analysis), or in which there was any crying or fussing. Therefore, all kinematic variables reported were computed in this 15 s window when the most active movements occurred.

Data from frames in which the markers were obscured were interpolated and all data were filtered using a 4^{th} order Butterworth filter. Kinematic variables (average speed, peak speed, active movement time, length of hand path, number of movement units, and jerk) were analyzed in these three phases of the development of infant arm movement in prehension. Active movement time was calculated by selecting the time when the movement speed was greater than 10% of the peak speed. The length of hand path was computed by summing the differences in hand position during the observation period (15s). Further, the length of hand path was also calculated separately along each axis - along the frontal axis(x),the sagittal axis(y) and the vertical axis (z). The hand path along the frontal axis(x), sagittal axis(y) and the vertical axis(z) were computed by summing the differences in hand position along frontal, sagittal and vertical axis correspondingly during the observation period (15s).

The number of movement units was defined using the inflexions in the speed profile. In this study, a single movement unit was defined when the difference between the local maxima and the two adjacent minima in the resultant speed profile was more than 1 cm/s (Thelen, Corbetta, & Spencer, 1996).

Jerk analysis. Mean squared jerk was calculated as the integral of square jerk with respect to time divided by the total movement time:

$$(1/\mathrm{MT})*\int_0^{MT}\frac{J(t)^2}{2}\,dt \qquad (1)$$

where MT is the duration of the movement (15s in the current study) and J(t) is the derivative of the recorded acceleration.

Finally, the dimensionless jerk was calculated as:

$$\sqrt{\int_0^{MT}\frac{J(t)^2}{2}dt*\left(\frac{MT^3}{V_{peak}^2}\right)} \qquad (2)$$

where MT is the duration of the movement, J(t) is the derivative of the recorded acceleration, and V_{peak} is the peak speed during the movement. In effect, this has the same term as the mean squared jerk, but instead of dividing by movement time, it is normalized by a quantity (MT^3/V^2_{peak}). This procedure makes the jerk dimensionless (i.e. unitless), thereby making the measurement of smoothness less biased with changes in the overall movement speed or movement time (Rohrer et al., 2002).

Statistical Analysis

A one-way repeated measure ANOVA on the factor of developmental age (3 levels – early, late and at the onset of reaching) was run for the dependent variables: average speed, peak speed, active movement time, length of hand path, number of movement units, and jerk. For the qualitative analysis, we compared only the early and late phases. Post- hoc comparisons were made using Tukey's post hoc test with the significance level was set at $p < .05$. In situations where sphericity was violated we employed the Greenhouse–Geisser correction.

Results

One infant was excluded from the analysis because of fussiness and crying. Another infant exhibited reaching at 12 weeks of age which meant that we did not have data for the early object-oriented phase. This participant's data were also not included for further analysis. Table 3.1 summarizes the number of the trials in which the infants were looking at the objects, the week of reach onset, and the hand used for reaching by each infant. The qualitative analysis showed that infants generally initiated goal-directed reaching movements between 14-16 weeks of age, while early object-oriented arm movements began between 10-12 weeks of age and late object-oriented arm movements started between 12-14 weeks of age.

Table 3.1. Descriptive statistics of the trials analyzed, includes the number of trials collected, the trials in which the infant was looking at the objects, the number of trials calculated, the week of reach onset, birth gestational age(BGA), birth weight (g) and the hand used for each infant.

Infant	# Collected trials	# Trials looking	# Calculated trials	Reach onset (weeks of age)	BGA	Birth weight(g)	Hand used
1	24	23	18	14	41	3180	R
2	35	32	8	14	41	3540	R
3	31	31	23	16	39	4220	L
4	35	30	17	16	39	4010	L
5	33	25	20	14	37	3090	R
6	27	21	9	16	41	3420	R
7	36	36	20	14	39	3230	R
8	25	20	12	14	40	2550	L

Qualitative analysis

The percentage of the 4 categories of the object-oriented arm movements (no movement, little movement, big movement, cross midline movement) as a function of early and late object-oriented arm movement category is shown in Figure 3.1. The inter-rater reliability between the two coders that classified the movements based on the 2D video data was generally high (the Kappa agreement was 0.81). There was no significant difference in the percentage of movements in the different categories between the early and late observations, $F(1,7) = 1.01$, $p = 0.35$.

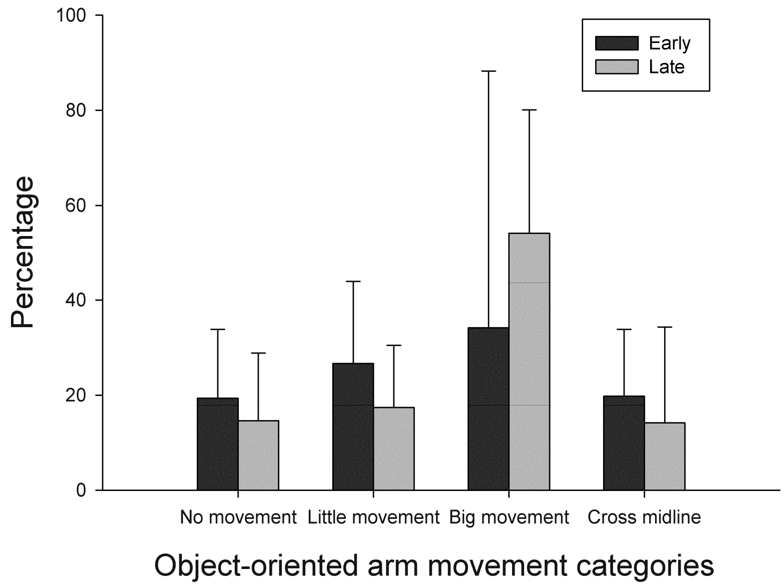

Figure 3.1. Percentage of the four categories of arm movements (no movement, little movement, big movement, cross midline movements) as a function of developmental age. Error bars represent one standard deviation (between-participant).

Kinematic analysis

The kinematic variables of the arm movements as a function of early, late object-oriented movement category and non-reaching movements are summarized in Table 3.2 One way repeated ANOVAs confirmed that there were no significant effects of developmental age for average speed, $F(2,14)=0.90$, $p=0.431$, peak speed, $F(2,14)= 0.25$, $p=0.672$, active movement time, $F(2,14)=1.29$, $p=0.305$, length of hand path, $F(2,14)=1.03$, $p=0.383$, number of movement units, $F(2,14)=0.08$, $p=0.927$. When we examined the hand paths along each axis, the length of the hand path along the sagittal axis(y), $F(2,14)=0.73$, $p=0.502$, and along the vertical axis(z), $F(2,14)=1.88$, $p=0.188$ also did not show significant changes. However, along the frontal axis(x), there was a significant difference, $F(2,14)=7.60$, $p=0.020$. Post-hoc comparisons showed a significant increase in the length of the hand path frontal axis in the non-reaching movement phase compared to early and late object-oriented movements. There was no statistically significant difference between the early and late object-oriented arm movement phases. Representative movement speed profiles from each phase of object-oriented movements are shown in Figure 3.2 Table 3.3 lists various kinematic measures computed for these two speed profiles.

Table 3.2. Mean (SD) kinematic measures as a function of developmental age.

Measure	Early Object-oriented Movement	Late Object-oriented Movement	Non-Reaching Movement
Average speed (cm/s)	7.34 (2.21)	6.84 (2.18)	7.60 (1.29)
No. of movement units	18.54 (2.20)	18.21 (2.99)	18.10 (1.02)
Path length (cm)	137.19(27.84)	123.36(33.99)	132.59(17.10)
Active movement time (s)	5.5 (1.31)	4.73 (0.78)	5.37 (0.73)
Mean squared jerk (cm^2/s^5)	1.9E+07(6.7E+06)	1.6E+07(9.3E+06)	1.5E+07(5.8E+06)
Dimensionless jerk	16423.27(4201)	13760.70(3735)	13236.30(1237)

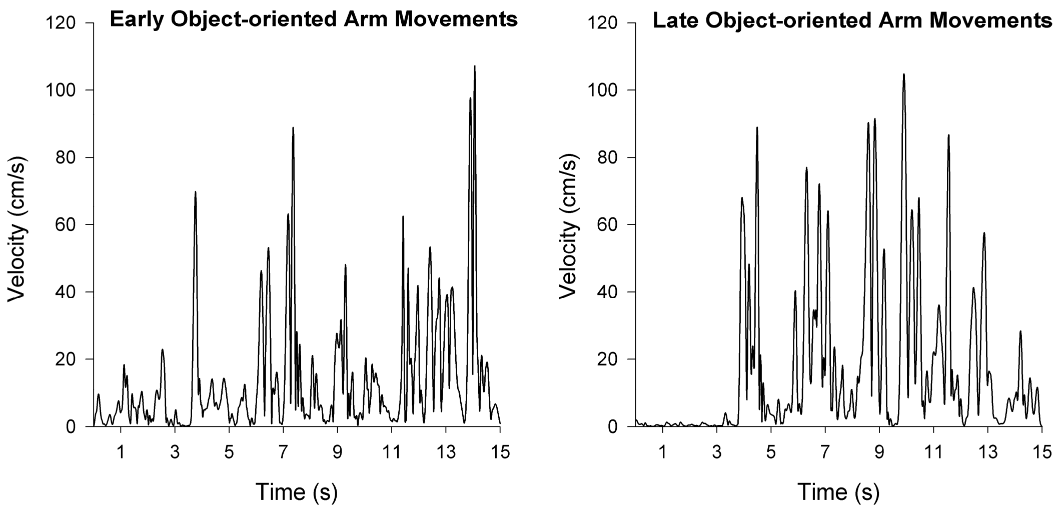

Figure 3. 2. Representative speed profiles from a single infant in each phase of object-oriented movements. Speed profiles were computed during a 15s window where the infant was most active.

Table 3.3. Kinematic measures computed for these two speed profiles.

Measure	Early Object-oriented Arm Movements	Late Object-oriented Arm Movements
Average speed (cm/s)	13.73	16.91
No. of movement units	23	21
Path length (cm)	230.34	263.93
Active movement time (s)	5.75	6.24
Mean squared jerk (cm^2/s^5)	4.55E+07	3.47E+07
Dimensionless jerk	14160.90	12654.71

Jerk measures

When we considered the mean squared jerk, there were no significant differences among the two phases of object-oriented movements and non-reaching movements for mean squared jerk, $F(2,14)=0.88$, $p=0.44$. However, when the dimensionless jerk was considered, there was a significant main effect of developmental age, $F(2,14)=5.40$, *p*=0.018. Post-hoc comparisons showed that the dimensionless jerk in the late object-oriented phase (M = 13760 SD = 4201) was significantly lower than early object-oriented movement phase (M= 16423 SD =3735). On the other hand, there was no statistically significant difference between late object-oriented to non-reaching movements. Taken together, the dimensionless jerk decreased from early to late object-oriented arm movement but there was no change after the onset of reaching. The individual dimensionless jerk for each infant as a function of developmental age is shown in Figure 3.3

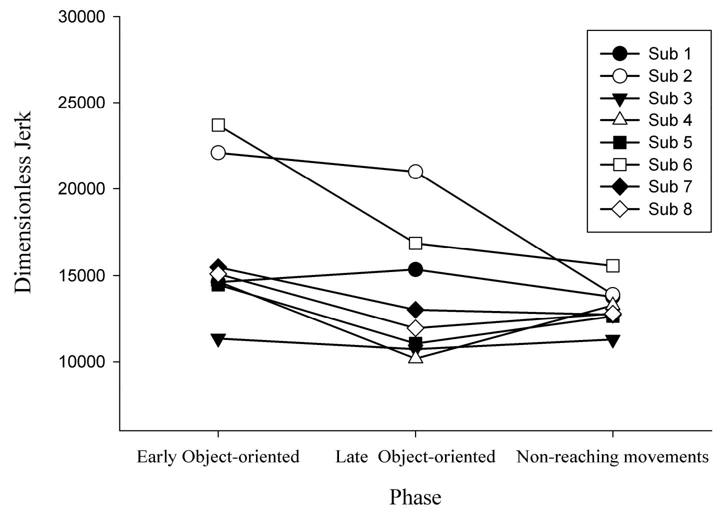

Figure 3.3. Dimensionless jerk as a function of developmental age (early, late object-oriented arm movement and non-reaching movement phases).

Discussion

The aim of this study was to quantitatively describe the qualitative properties that precede the transition from object-oriented arm movements to goal-directed reaching movements in infancy. This movement transition is one of the fundamental qualitative changes in the development of prehension in infancy (Adolph & Berger, 2005; Gesell, 1929). Our findings clearly showed that the standard kinematic variables used to investigate the development of the reaching component of prehension, namely average speed, peak speed, actively movement time, movement path length and number of movement units (Berthier & Keen, 2006; Konczak & Dichgans, 1997, Thelen et al., 1993) did not reveal changes from early object-oriented arm movements to late object-oriented arm movements. Further, qualitative analysis of these movements could also not distinguish between the two phases although some studies have reported changes in interjoint coordination changes in early pre-reaching movements (Lee et al., 2008). However, the variable of dimensionless jerk captured the changes in the transition of the early and late phases of object-oriented arm movements. The decrease in jerk is consistent with an earlier study by Berthier and Keen (2006) who showed that in *actual* reaching movements (in contrast to object-oriented movements), the total jerk decreased more dramatically with age than other kinematic variables such as average speed or peak speed.

Of the three components that constitute the dimensionless jerk (integrated squared jerk, movement time and peak speed), one component i.e., movement time was always constant (i.e., 15 s) and did not contribute to the changes observed. Neither the mean squared jerk (which in this case was the integrated squared jerk divided by a constant MT) nor the peak speed by itself showed a significant change from early to late object-oriented movements. However, when they were used in combination in the dimensionless jerk measure, there was a significant decrease from early to late object-oriented movements. This suggests that some of the between-subject variation in the integrated squared jerk was due to changes in absolute magnitude of speed and not necessarily the smoothness of the speed profile.

Previous studies have examined the variable of movement speed as a critical variable mediating the transition from object-oriented movements to reaching. However, the findings from these studies have generally not been conclusive. Thelen et al. (1993) found that 2 weeks before reach onset, infants either sped up or slowed down their movement speed. In contrast, Bhat and Galloway (2006, “toy condition”) found that infants increased their movement speed right before the reach onset. In the current study, we did not find any consistent changes in the movement speed from early to late object-oriented arm movement phase. Some of these discrepancies across studies may be due to differences in the definition of the onset of reaching. More specifically, in the current study, the onset of reaching was defined as the first week in which infants contacted the toy whereas Bhat and Galloway (2006) defined the onset time as the first week that total toy contacts were three times greater than any previous week. Therefore, Bhat and Galloway’s (2006) criterion for the onset of reaching was probably later in developmental time and could reflect changes that occur after those observed in the current study.

With regard to movement smoothness, the smoothness of movement is typically indexed by the number of movement units (von Hosten, 1991). However, the number of movement units is defined using an arbitrary threshold (e.g., 1 cm/s) on the speed profile. In contrast, the dimensionless jerk is computed using the entire speed profile without having to use an arbitrary threshold. Other attempts to quantify smoothness have used the integrated squared jerk (e.g., Berthier & Keen, 2006). However, the integrated squared jerk is an un-normalized measure which would be affected by not only changes in smoothness of the movement but also by changes in the absolute values of movement amplitude, speed, and time (Hogan & Sternad, 2009). It has been previously shown that the characteristics of infant object-oriented arm movements may have different amplitudes, number of bounds, and movement speeds (Thelen et al., 1993). As a consequence, in this study we took advantage of the fact that dimensionless jerk is more consistent with the construct of movement smoothness and shows more consistent trends with changes in movement amplitude, multiple speed peaks or periods of arrest (Hogan & Sternad, 2009). These properties raise the possibility that the dimensionless jerk could be a useful measure clinically to detect neurological dysfunction in early infancy with greater sensitivity (Prechtl, 1990).

The decrease in jerk considered in conjunction with previous findings (Wann, 1987; Rohrer et al., 2004) leads to the suggestion that the changes in the smoothness of movements in the development of prehension reflect the change from early object-oriented arm movements that are composed of a number of submovements to a later phase, where those submovements become blended during development. This is also consistent with the hypothesis of Berthier and Keen (2006) who suggested that the decrease in reaching speed and jerk may be a consequence of increasing ability to modulate net joint torque through anticipation of motion-dependent torques and by more appropriately timing muscle contractions (Berthier & Keen, 2006; Konczak et al., 1995; Konczak & Dichgans, 1997). This improved ability to modulate torque may also be correlated with changes in muscle strength (Thelen, 1983; Adolph, Vereijken, & Shrout, 2003). Initially, the infants may lack sufficient muscle strength to lift their arm against gravity resulting in multiple submovements (Thelen et al., 1984). But once the infants gain more muscle strength, they may be able to generate the forces required to achieve greater control of the limb during reaching movements.

Though the nature of the findings reported in the current study are preliminary, the inherent variability in speed and direction of pre-reaching movements poses a challenge to investigators. In particular, comparison of the trends in kinematic variables across different studies is difficult because of discrepancies in defining and analyzing pre-reaching movements. For example, some investigators (e.g., Bhat & Galloway, 2006) decompose the oscillatory movement of the arm into several movement cycles whereas in the current study, we considered the oscillatory movement as a single movement. These issues are theoretically linked to the relation between rhythmic and discrete movements (e.g., Schaal, Sternad, Osu, & Kawato, 2004) and may need to be explored in greater detail in future studies.

Finally, although the current study was not designed to distinguish between competing hypotheses regarding the function of object-oriented movements, the finding that object-oriented movements undergo systematic changes before the onset of reaching is most consistent with the hypothesis that these arm movements serve as a means to explore the environment (E. J. Gibson, 1988, 1997). In particular, the higher jerk observed early in development suggests that infants actively explore the possibility for action in the environment, and subsequently the primitive form of these object-oriented arm movements is developed into more skilled goal-directed reaching movements (Konczak & Dichgans, 1997). The importance of exploratory behavior has also been shown by Needham and colleagues (Libertus & Needham, 2010; Needham, Barrett, & Peterman, 2002) who increased exploratory behavior in infants by having them pick up objects using "sticky mittens" (i.e., Velcro-palmed mittens). After 2 weeks of training, they found that infants not only used improved visual strategies when objects were presented, but were also engaged in more object exploration and advanced reaching compared to a control group that did not receive such training. Such exploratory behavior may therefore be critical for the development of reaching behavior. Although more direct tests of this hypothesis are required, our results show that these subtle changes in infant motor behavior are likely to be reflected in measures such as dimensionless jerk that take into account the entire shape of the speed profile.

CHAPTER 4: AUDITORY FEEDBACK OF EXPLORATORY ARM MOVEMENTS FACILITATES THE DEVELOPMENT OF REACHING IN INFANCY

Abstract

The purpose of this study was to investigate the influence of auditory feedback on the development of infant reaching movements. Eleven full-term infants were observed biweekly from the age of 10 weeks to the onset of goal-directed hand movements. Auditory feedback was provided contingent on the infants moving their arms. There were three conditions: 1) no audio feedback, 2) the mother's voice, and 3) different musical tones. Kinematic data of the arm movements were recorded. The results showed that before the onset of reaching, the amplitude of arm movement increased when auditory feedback (mother's voice and musical tones) was provided. Also, at the time point of reaching onset, the number of reaches increased when the auditory feedback was presented. Thus, infants are able to use auditory feedback to explore the possibilities for action before the onset of reaching, and subsequently the primitive form of these object-oriented arm movements is developed into more skilled goal-directed reaching movements.

Introduction

The emergence of fundamental movement patterns during infancy is one of the central issues in the study of motor development. Waddington's (1957) epigenetic landscape has provided a useful metaphor to explain the development of those fundamental movement patterns. That is, the developing system is searching for goal-relevant action solutions in the probabilistic state space of the attractor dynamics. The organism, task, and environmental constraints interact to construct the evolving formation of the dynamical landscape (Newell, Liu, & Mayer-Kress, 2003).

Gibson (1979) introduced the idea of affordances of the environment as "what it offers the animal, what it provides or furnishes, either for good or ill". In this framework, objects in the environment are not perceived in terms of their physical properties such as size or shape, but in terms of the possibilities for action relative to the perceiver. That is, infants are capable of regulating their behavior according to what information is available in their environment. Siqueland and DeLucia (1969) showed that when infants' sucking behavior controlled the illumination of a visual display, they would suck with greater intensity and frequency to obtain the visual stimulation. This study illustrated that the developing system searches in the perceptual-motor workspace and the perceived information (visual display) influences the action (sucking patterns). This is in line with the ecological approach to perception and action; that is, the development of movement acquisition is a result of the fit between the behavior-relevant properties of the organism in relation to information in the surrounding environment and the task demands (Gibson, 1979; Adolph & Berger, 2006; Warren, 1984).

Arm movements emerge early in life – after the ninth gestational week the arm movements of a fetus can be observed (Prechtl, 1997). Newborn infants show repeated, short bouts of arm movements. These movements have been termed ‘spontaneous’ or ‘stereotypy’ movements, such as arm waving and banging. Thelen (1979, 1981) claimed that the trajectory of spontaneous movement development coincides with emergent voluntary control, meaning arm waving coincides with emergent reaching and arm banging precedes manipulatory control of the hand. In other words, spontaneous arm movements are a primitive form of more advanced movements such as reaching and grasping.

Previous studies have demonstrated that the structure of these seemingly unorganized movement patterns can be modulated by the influence of postures changes (Kaiwai, Savelsbergh, & Wimmers, 1999), alertness, social interaction (Thelen, 1981), the characteristics of the object presented (Bhat & Galloway, 2005), enriched experience (Libertus & Needham, 2010; Needham, Barrett, & Peterman, 2002) and reinforcement (Rovee-Collier & Gekoski, 1979; Rovee-Collier & Capatides, 1979; Chen, Fetters, Holt, & Saltzman, 2002). Indeed, infants are actively involved in the exploratory activity through which they realize perception-action sequences (E.J Gibson, 2000). In the mobile paradigm (Rovee-Collier & Gekoski, 1979; Rovee-Collier & Capatides, 1979), for example, infants actively control the movement of a mobile suspended over the crib by increasing their kicking frequency. They can even modulate their kicking movements into a certain pattern (joint angle) to control the mobile (Angulo-Kinzler, 2001; Angulo-Kinzler & Horn, 2001; Angulo-Kinzler, Ulrich, & Thelen, 2002; Chen, Fetters, Holt & Saltzman, 2002).

These findings are consistent with the perspective that the development of movement acquisition is influenced by interactions among the organism, task, and environmental constraints (Newell, 1986). The development of movement acquisition is a process of mapping the perception information flows and the action energetic flows in the perceptual-motor workspace (Fowler & Turvey, 1978; Newell & McDonald, 1992). In this view, movement patterns are emergent properties of the constraints imposed on the action rather than products of prescriptions for action (Kugler, Kelso, & Turvey, 1982). The constraints on the action provide boundary conditions that serve as a principle for organizing the coordination (Newell, 1986). In other words, within the boundary conditions there are many potential action solutions; the action thus emerges from the interactions of the organism, task, and environmental constraints.

Little is known, however, about the influence of auditory feedback on the development of reaching movements. Darcheville, Boyer, and Miossec (2004) showed that the number of reach responses was higher when the mother's voice was provided and the sensor attached to the infant's hand was within the reaching place (the reaching place was defined as a virtual location above the infant's right ear). Bhat and Galloway (2006) found that infants showed different arm movement patterns depending on whether or not an object was presented. Also, Needham and colleagues increased infants' exploratory behavior by having them pick up objects using "sticky mittens"; with 2 weeks of training the infants showed improvements not only in their reaching skill but also in visual strategies (Libertus & Needham, 2010; Needham, Barrett, & Peterman, 2002).

Dibiasi and Einspieler (2002) found that unanimated acoustic stimulation and interaction with the mother did not change the pattern of spontaneous arm movements in

12-week-old infants. One possible explanation for this result is that the acoustic feedback provided in Dibiasi and Einspieler's study was not associated with the infants' arm movements. The acoustic feedback was a tape-recorded series of sounds that was played for 5s with an interval of 10s, without reference to the dynamics of the infants' arm movements.

The findings suggest that the presentation of the object and concurrent feedback mediate movement patterns in the early exploratory phase of the development of reaching in early infancy. The present study investigated whether real-time concurrent auditory feedback influences the development of reaching in infancy, and if it can, whether there is any difference in the efficacy of different kinds of auditory feedback (the mother's voice vs. musical tones). A related question was whether the feedback induced exploratory arm movements influenced the subsequent onset of reaching movements to an object.

Methods

Participants

The participants were 11 healthy full-term infants (6 male). Each infant started the first testing session at 10 weeks of age and was tested subsequently at two-week intervals until 16 weeks of age. Informed parental consent was approved by The Pennsylvania State University Human Subjects Review Board.

Apparatus

The infants were seated in an infant chair at a 30° recline from vertical; a seat belt held them in a stable seated posture but allowed them to move their arms and legs freely. Loudspeakers were placed beside the infant chair. Data were collected using a 4-camera (Sampling rate = 240 Hz) motion analysis system (Qualisys Motion Capture Systems, Gothenburg, Sweden) and two video recorders (Sampling rate = 60 Hz). For the motion analysis system, two cameras were positioned on the right of the infant and two cameras on the left. The average measurement error for this calibrated volume was < 0.5 mm. For the video system, one video recorder was strutted by a tripod hanging above the chair to capture prehensile behavior on the transverse plane (i.e., a top-down view); the other one was used to capture eye movements. The motion analysis and the video camera systems were synchronized with an external LED that was triggered by the motion analysis system.

There were two computers: marker positions from the Qualisys Motion Capture System (Sampling rate = 240 Hz) were received by a host computer, and the marker data were transferred to a client computer via an Ethernet crossover cable which use a customized program in C++ . The mother's voice was provided when the marker on the wrist was moving more than 10 mm in 250 ms. This criterion was based on the changes in the positions. The minimum duration of the feedback was 2s. For the musical tone condition, before the experiment, the maximal range of the motion was calculated for each axis and a 7 × 7 × 7 grid was constructed in a 3D space. Whenever the marker moved into a different grid, a musical tone was played for that grid. The idea was that if the infant moved in a different grid, different musical tones were provided. The blocks of the 7 × 7× 7 grid were assigned different musical tones (do re mi fa so la ti).

Procedure

Prior to the start of the experiment, joint markers were attached to the right-hand side of the participant's body. These markers (10 mm in diameter) were made from black felt and were attached to the infant's wrist, forearm, and upper arm via hypoallergenic tape. A 1" cube was presented to the infants on the open palm of the experimenter on their right-hand side within reaching distance to prompt right-hand reaching. There were 3 auditory feedback conditions: no auditory feedback (baseline condition), the mother's voice, and different musical tones. Each condition lasted for 60 s and was repeated twice, starting with one trial of no auditory feedback, followed by 2 trials of the mother's voice or musical tone, and ending with one trial of the no auditory feedback condition. The order of the mother's voice and musical tone conditions was counterbalanced across participants.

Data Analysis

The participant's object-oriented arm movements were divided into five categories: (1) no movement, where the participant did not move his/her arm; (2) little movement, where the participant moved his/her arm with a small range of motion (only lower arm movements); (3) big movements, where the participant moved his/her arm with a big range of motion (both lower and upper arm movements) but did not cross the midline toward the presented object; (4) toward the object movement, where the participant moved his/her arm toward to the object but did not make contact with it; and (5) reach, where the participant made contact with the presented object (Berthier & Keen, 2006; Carrico & Berthier, 2008; Thelen et al., 1993). These movements were coded independently by two raters who each classified all the trials.

Data were selected for kinematic analysis based on the following criteria: 1) from the 60 s observation period, we selected the 15 s duration in which there was the most active hand movements (which was identified from the 2D camera and the speed profile from the motion analysis); and 2) the infants were looking at the object and/or noticed it before reaching (Corbetta & Thelen, 1995). Data from frames in which the markers were obscured were interpolated and all data were filtered using a 4^{th} order Butterworth filter. The kinematic variable of the length of the hand path was analyzed. The length of the hand path was computed by summing the differences in hand position during the observation period (15 s).

A mixed modeling approach (PROC MIXED using SAS) based on the factor of auditory feedback (no audio feedback, the mother's voice, musical tone) was run for the dependent variables of week of reach onset and number of reaching movements. The determination of the model fit was based on: 1) model convergence, 2) a positive definite G matrix, and 3) the statistical fit comparison based on the Akaike Information Criteria (Littell, Milliken, & Stroup, 2006). For the non-active movement analysis, a one-way repeated measure ANOVA based on the factor of auditory feedback was run for the dependent variable of movement category of quiet movement. For the kinematic analysis, a one-way ANOVA based on the factor of auditory feedback was run on the dependent variable of length of the hand path. Post hoc comparisons were made using Tukey's post hoc test with the significance level set at $p < .05$.

Results

Qualitative analysis

The percentage of occurrences of each arm movement category as a function of auditory feedback is depicted in Figure 4.1 The inter-rater reliability between the two coders that classified the movements based on the 2D video data was generally high (the Kappa agreement was 0.82). There was no significant difference in the week of reach onset ($p > 0.5$). That is, infants initially reached for the object at about the same age in the 3 different auditory conditions (no auditory feedback, M = 15.60 weeks, SD = 2.09, mother's voice, M = 14.39 weeks, SD = 1.70, musical tone, M = 13.98 weeks, SD= 1.70).

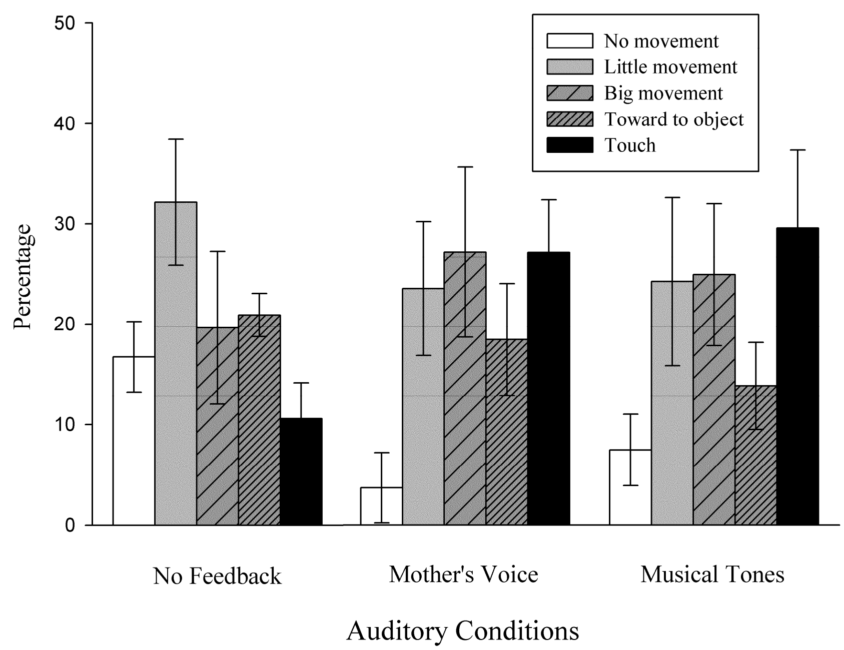

Figure 4.1. The percentage of occurrence of each arm movement category as a function of auditory feedback. Error bars represent one standard error (between-participant).

However, there was a significant difference in the percentage of reach movements as a function of auditory feedback ($p = 0.002$). Post-hoc comparisons showed the percentages of reach movements were significantly higher for the mother's voice and the musical tone conditions. A one-way repeated ANOVA confirmed that there was a significant main effect of auditory feedback, F (2, 16) = 4.58, p = 0.018 on arm movement activity. Post-hoc comparisons showed that the percentage of no movement was significantly higher in the no auditory condition (M = 16.73, SD = 11.16) than in the other 2 auditory conditions (mother's voice, M = 3.70, SD = 11.10, musical tone, M = 7.47, SD = 11.28).

Kinematic analysis

There was a significant difference in the kinematic variable of the length of hand path as a function of auditory feedback, F (2, 16) = 8.06, p = 0.004. Post-hoc comparisons showed that the length of the hand path in the no auditory condition (M = 105.97 cm, SD = 23.34) was significantly shorter than in the other 2 auditory conditions. However, there was no statistically significant difference between the mother's voice and the musical tones condition (mother's voice, M = 137.87 cm, SD = 27.35, musical tone, M = 125.44 SD = 28.83) (see Figure 4.2).

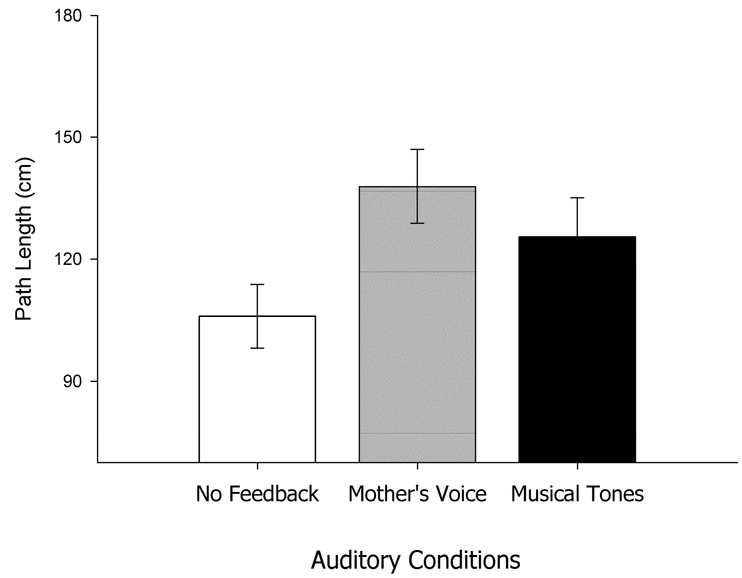

Figure 4.2. The length of the hand path as a function of auditory feedback. Error bars represent one standard error (between-participant).

Taken together, these results show that auditory feedback did not affect the onset time of reaching, but when auditory feedback was presented, infants' arm movement were more active, and this resulted in a higher percentage of reaching movements. However, there was no significant difference in the efficacy of the different kinds of auditory feedback (mother's voice vs. musical tone).

Discussion

A central feature of the study of motor development is the determination of the control parameters and goal states that channel the relevant behavioral change (Newell et al., 2003). In the current study, we investigated the influence of auditory feedback on the development of exploratory movement that relate to the onset of reaching movements.

The results showed that augmented auditory feedback influenced the development of reaching in infancy. When concurrent auditory feedback was provided, infants were more likely to move their arms to explore the possibilities for action, and furthermore these exploratory behaviors brought the arm closer to the presented object.

These findings are in line with Gibson's (1979) idea that, "We must perceive in order to move, but we must also move in order to perceive" (p. 223). That is, movement patterns emerge in the perception–action loop by generating information for perceptual systems and bringing the matching sensory apparatus to the available information (Adolph & Berger, 2005). In this study, infants first perceived the object and then initiated their arm movements, and by moving their arms, they perceived the auditory feedback at the same time, which enhanced the exploratory arm movements. The concurrent auditory feedback provided a perceptual-motor workspace that continually evolved while the infants were in search of task solutions (Fowler & Turvey, 1978; Newell et al., 1989).

Pavlov (1927) and Skinner (1953) proposed that development is a function of learning. This view helped shift the focus of infant motor development from the maturational development of the organism to the role of external factors such as the environment (Zelazo, Zelazo, & Kolb, 1972). Some studies addressed the learning effect by applying "enhanced practice". Researchers have trained infants to crawl for 15 min a day over a 3-week period. They found that the training group showed advanced crawling movements earlier than the controls (who received no training) (Lagerspetz et al., 1971). The ecological perspective further highlights the importance of perceived information; that is, development is a process of learning to perceive affordances (E.J, Gibson, 1988).

Affordance (Gibson, 1979) refers to an animal-environment fit; therefore, the development of movement acquisition is the process of searching for the available information that the environment offers.

The findings of current study also supported the view that the early arm exploratory movements are important precursors to the development of reaching. That is, the function of these exploratory arm movements helps the infants in developing a reference for reaching movement (Jones & Lederman, 2006). The emergence of the reaching movement was through repeated explorations of the task in the perception-motor space. As infants produce exploratory arm movements, these movements are accompanied by changes in posture and in the concomitant information about the hand position related to the object. Also, these repeated exploratory arm movements increase the muscle strength of the relevant effectors unit. Thus, the developmental trajectory of the reaching movement acquisition is a searching for a solution through the early exploratory arm movements (Thelen, 1990).

The comparison of the efficacy of the different kinds of auditory feedback showed that infants performed equally well in the mother's voice and musical tone conditions. There is evidence that infants prefer their mother's voice to that of other females (DeCasper & Fifer, 1980). We found that the musical tone feedback was attractive to infants. In the musical tone condition, the whole perceptual-motor workspace was like a virtual piano: as infants moved their arms in different spaces, different musical tones were provided in real time. Therefore, the different forms of auditory feedback (mother's voice and musical tone) functioned in the same way.

The current study showed that auditory feedback facilitated the exploratory behavior that precedes the onset of reaching but did not accelerate the onset time of reaching. In auditory feedback conditions, infants were more likely to move their arms to explore the possibilities for action that subsequently resulted in a higher reaching frequency. The changes in the movement activity and amplitude during the observation period may explain the transitory effect of the concurrent auditory feedback. However exploratory, this study may offer some insight into how infants use the auditory feedback to modulate their arm movement. Further research may use this experimental design to examine whether with practice, the use the auditory feedback can accelerate the onset time of reaching.

This finding is consistent with the affordance idea that the organism searches for the fit between its action and the information available in the environment. In other words, the auditory feedback was provided when the infants moved their arms. However, acquiring the auditory feedback was not dependent on the forms of the arm movements, and this is perhaps why we only found changes in movement amplitude. Future studies are needed to confirm whether auditory feedback can modulate infants' movement into a certain pattern. For example, the auditory feedback is only provided when the infants move their arms in a certain direction or space-time pattern.

In sum, the current study supports the importance of exploratory behavior in early infancy (E.J Gibson, 1988), and how exploratory behavior can be channeled through concurrent auditory feedback. An implication for clinical populations may be to apply auditory feedback to facilitate development. On the other hand, this experimental setup provides a potential vehicle to further investigate whether infants can modulate their movements into a certain pattern to obtain the information.

CHAPTER 5: VISUAL FEEDBACK OF HAND TRAJECTORY AND THE DEVELOPMENT OF INFANT PREHENSION

Abstract

The purpose of this longitudinal infant study was to investigate the influence of visual information of the hand trajectory in the development of reaching movements in prehension. Ten infants were observed biweekly from the age of 10 weeks to 28 weeks, and at 1 yr. The reach kinematics were analyzed at age of reach onset, 6 mo and 1 yr of age. The results showed that infants reached for objects earlier when the visual feedback of the hand trajectory and the object were available. However, visual feedback of the hand trajectory did not change the movement speed and smoothness of the reach component at 6 mo and 1 yr of age. Infants reached a larger object earlier and with higher velocity than for a smaller object. The results reveal that visual feedback of the hand trajectory and the size of object influenced the development of prehension.

Introduction

The development of perception and action in infants holds mutual influences on behavior. In this sense, the study of the interaction between visual information and prehension (reaching and grasping) in infancy opens a window to understanding the development of movement coordination. The development of prehension has been divided into visually triggered and visually guided reaching behavior based on the time course of the hand movements (Clifton, Rochat, Robin, & Berthier, 1994; Clifton, Muir, Ashmead, & Clarkson, 1993; Laskey, 1977; Piaget, 1952).

In the early stages of the development of reaching behavior, it has been hypothesized that the reach movement is visually triggered, that is, the visual information about the location of the target is used to initiate the movement (Trevarthen, 1984). In this view, the position of the object is perceived visually, while the position of the arm is perceived proprioceptively. On the other hand, the last part of the reach trajectory where the hand approaches and contacts an object is considered to be visually guided. In this case, the position of the arm is perceived visually with reference to the target, allowing precise adjustments to be made to ensure the accuracy of the reaching and grasping components (Jones & Lederman, 2006).

This classification of two categories of visual control is similar to that used in the classic study on the development of visual control of limbs in kittens (Hein & Held, 1967) where visually triggered was defined as lowering the kitten toward a continuous surface (no accuracy was required). In contrast, visually guided was defined as lowering the kitten toward a discontinuous surface, in which visually guided placing accuracy to hit a prong was required. In the experiment where the kitten's vision of their own limb was occluded or not, it was shown that visually triggered paw extension developed without sight, but visually guided paw placing required prolonged viewing of the limbs. These results provided an early indication that the sight of the limb has an impact on the accuracy of the final reaching movement but not for the reaching initiation.

In contrast, it has been shown that infants at an age as early 3 to 5 days old are able to use the vision of their own hand movements to control the reach trajectory. It was shown that neonates have some control of their own spontaneous movement even at an early age when visual feedback of the arm is available (van der Meer, van der Weel, & Lee, 1995). Previously, Gesell and Ames (1947) used cinema-analysis to observe infants' arm movements from 16 through 60 weeks of age. It was shown that infants moved their arm more actively when a mirror was presented in front of the infants. Indeed, in this mixed cross-sectional and longitudinal design, the hand and arm movements did not change in a monotonic fashion; instead, there was a discontinuous progression and regression of prehensile activity level of the hand and arm movements.

Thus, there are two primary and contrasting views as to the role of visually guided reaching in infancy. One viewpoint holds that reaching is planned before it is executed so that, for example, visual guidance of the hand is not necessary to achieve object contact (Clifton et al., 1993). A second viewpoint is that infants need the online vision of their hand to reach and contact the object (Piaget, 1952; Clifton, Perris, & Bullinger, 1991). There is evidence for both points of view.

It has been shown that infants do not need to see their hand to reach and contact an object (Clifton et al., 1993; Clifton et al., 1994). In a longitudinal study, Clifton et al. (1993) recorded the emergence of reaching for objects by 6- to 25-week-old infants in three different conditions, natural light, when the object was glowing against a dark background, and glowing also with auditory cues in complete darkness. The results showed that the onset time of infants' first contact with the object was at about the same age in all conditions (mean age of light, 12.3 weeks, and for dark, 11.9 weeks). In another study, the reaching trajectory in 6-month-old infants showed a similar movement speed profile to the hand trajectory regardless of the presence or absence of vision of the hand (Clifton et al., 1994).

In contrast to these results, and as mentioned above, 3 to 5 day-old babies are able to control their hand movements when vision of the hand is available (van der Meer et al., 1995). Also, Laskey (1977) occluded sight of body and hand by an apparatus and found that 5 1/2 to 6 1/2 month-old infants' reaching was compromised without the sight of their hand movement, but that the prehension of 4 1/2-month-olds infants was less affected. In Berthier and Carrico's (2010) cross-sectional study, they found that 6 month-old infants reached faster in the dark, whereas, one-year-old infants reached faster in the light. Taken together, these findings imply that there are age-related discontinuities in the use of visually guided reaching in infancy.

It appears that visual guidance facilitates reaching in newborns, but does not affect the onset time of reaching in infants until about 12 weeks old, and then at 5 1/2 to 6 1/2 months, where visually guided movement once again enhances the reaching behavior. However, without a systematic experimental investigation of this potential discontinuous developmental trend it is premature to draw this conclusion. Therefore, the main question investigated in this study was to examine in a longitudinal study the time course of the impact of visual information of the hand trajectory and for the object in the development of prehension in infancy. If the visual feedback modulates the development of prehension behavior then providing or enhancing the feedback at critical time points in development may facilitate the prehension behavior (Bushnell, 1985).

The development of the infant hand movements is not determined solely by the influence of a single factor such as the presence or absence of vision. For example, several studies have shown that infant grip configurations are also influenced by the properties of the objects they are reaching for (shape, size and texture) (Lee, Liu, & Newell, 2006; Newell, McDonald, & Baillargeon, 1993; Newell, Scully, Tenenbaum, & Hardiman, 1989; Siddiqui, 1995). Indeed, object properties play an important role in mediating the development of infant grip configurations. Therefore, in this study we also manipulated the object properties by changing the size and shape of the objects to be grasped.

Methods

Participants

The participants were 10 healthy full-term infants (5 female). The first testing session was at 10 weeks old and participants were tested at two week intervals until the age 28 weeks and once at 1 yr of age. Infants in each testing session were tested about 1 hr before an anticipated feeding (Thelen, Fisher, & Ridley-Johnson, 1984). Informed parental consent was approved by The Pennsylvania State University Human Subjects Review Board.

Apparatus

Infants were seated in an infant chair at 30° reclined from the vertical with a seat belt that held them in a stable seated posture but allowed them to move their arms and legs freely. Data were collected using a 4- camera (Sampling rate = 240 Hz) motion analysis system (Qualisys Motion Capture Systems, Gothenburg, Sweden) and two video recorders (Sampling rate = 60 Hz). The two video systems were synchronized by using an external LED that was triggered by the motion analysis system. For the motion analysis system, two cameras were positioned on the right of the infant and two cameras on the left. The average measurement error for this calibrated volume was < 0.5 mm. For the video system, one video recorder was strutted by a tripod hanging above the chair to capture prehensile behavior on the transverse plane (i.e., a top-down view); the other one was used to capture eye movements.

Procedure

Prior to the start of the experiment, joint markers were attached to both sides of the participant's body. These markers (10 mm in diameter) made from black felt cloth were attached to the infants' right and left wrist, forearm, and upper arm via hypoallergenic tape. A pacifier (size 2 for newborns) and cubes in two sizes (1" and 2" in diameter) were presented to the infants. The objects were on the opened palm of the experimenter and presented on the midline and in reaching distance of the infant. There were two conditions of visual feedback of the infant's hand. The visual feedback of the hand was controlled with a cloth texture barrier which blocked the view of the hand. In one condition (vision: no barrier), the infant could see the entire movement of his/her hand.

In the other condition (no vision: with barrier) the infant could not see his/her hand. However, in both conditions, the infant could see the location of the object and when the hand contacted the object.

Each object and vision condition was repeated twice, and each time, either one of two cubes or the pacifier was placed within the infant's reach in a random order but was blocked within the respective visual feedback condition. Each trial was 30 s long or until the infant grasped the object.

Data Analysis

For qualitative analysis, hand movement data were classified into 5 categories: no reach, one hand reach, two hand reach, one hand grasp, and two hand grasp. The distinction between the touch and grasp was defined by whether the infants lifted the object or not (Lee et al., 2006). The classification and frequency of occurrence of hand movements were coded by two independent observers. For quantitative analysis, kinematic variables (average speed, number of movement units, straightness of the reach and jerk) were analyzed on the reach trials. Kinematic data at reach onset, 6 mo and 1 yr of age were compared to examine the influence of visual feedback of the arm trajectory and object size on the development of prehension. Reach was defined as the hand moving toward to the object and accompanied by contact with the presented object. Therefore, the reach onset was defined as the first week in which the infant made contact with the presented object (Berthier & Keen, 2006; Carrico & Berthier, 2008; Thelen et al., 1993).

Data from frames in which the markers were obscured were interpolated and all data were filtered using a 4th order Butterworth filter. The number of movement units was defined using the inflexions in the speed profile of the reach trajectory. In this study, a single movement unit was defined when the difference between the local maxima and the two adjacent minima in the resultant speed profile was more than 1 cm/s (Thelen, Corbetta, & Spencer, 1996). Straightness was the ratio of the total length of hand trajectory and the distance between the positions of the hand initiation to the object contact, thus, the quotient of 1 represents a straight-line hand path (Konczak, Borutta, & Dichgans, 1995).

Jerk analysis

Mean squared jerk was calculated as the integral of square jerk with respect to time divided by the total movement time:

$$(1/\mathrm{MT})*\int_0^{MT} \frac{J(t)^2}{2}\,dt \qquad (1)$$

where MT is the duration of the movement and J(t) is the derivative of the recorded acceleration.

In addition, dimensionless jerk was calculated as:

$$\sqrt{\int_0^{MT} \frac{J(t)^2}{2}\,dt * \left(\frac{MT^3}{V_{peak}^2}\right)} \qquad (2)$$

where MT is the duration of the movement, J(t) is the derivative of the recorded acceleration, and V_{peak} is the peak speed during the movement. In effect, this has the same term as the mean squared jerk, but instead of dividing by movement time, it is normalized by a quantity (MT^3/V^2_{peak}). This procedure makes the jerk dimensionless (i.e.

unitless), thereby making the measurement of smoothness less biased with changes in the overall movement speed or movement time (Rohrer et al., 2002).

Statistical Analysis

For qualitative analysis, a two-way repeated measure ANOVA was performed on the reach onset phase. The factors were feedback of the arm trajectory (vision, no vision) and object size (pacifier, 1” cube, and 2” cube). For quantitative analysis, a mixed modeling approach (PROC MIXED using SAS) was used to perform on the factor of age (reach onset, 6 mo and 1 yr of age) and was run for the dependent variables: average speed, number of movement units, straightness of the reach, and jerk. Determination of model fit was based on: 1) model convergence, 2) a positive definite G matrix, and 3) statistical fit comparison using Akaike Information Criteria (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006). Post hoc comparisons were made using Tukey’s post hoc test with the significance level set at $p < .05$.

Results

All participants completed all of the testing sessions of the longitudinal study but two infants missed one session (one missed the session at 1 yr of age, the other one missed the session at 6 mo of age) due to family events. Figure 5.1 shows the age of reach onset as a function of vision condition and object size.

The two-way repeated (vision × size) ANOVA revealed a significant main effect of vision condition, $F(1,9) = 7.52$, $p = 0.023$, and object size, $F(2,18) = 4.95$, $p = 0.019$. Infants reached for the object earlier in the vision condition (M= 15.60 weeks, SD =1.34) than in the no vision condition (M = 17.87 weeks, SD = 2.93). Post hoc comparisons showed that infants reached for the biggest object (2" cube, M= 16.10 weeks, SD = 2.12) earlier than the smallest object (pacifier, M = 17.60 weeks, SD = 2.38) but these objects were not significantly different to the median size object (1" cube, M = 16.5 weeks, SD = 1.65).

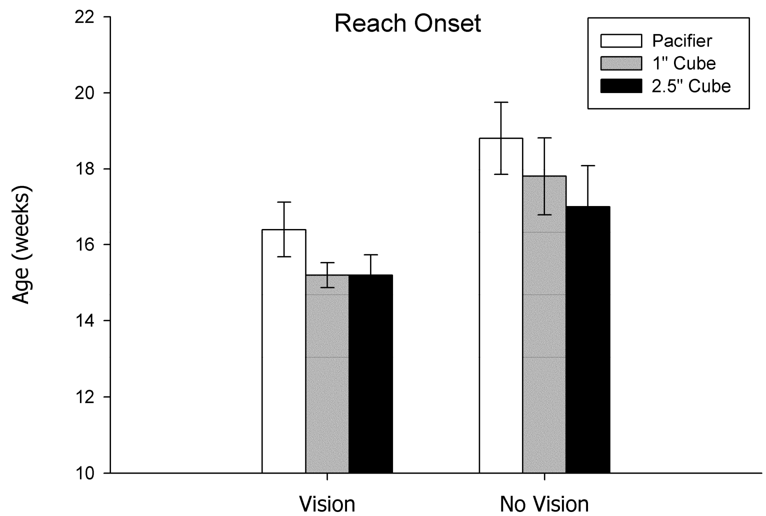

Figure 5. 1. Age of reach onset as a function of vision condition, and object size. Error bars represent one standard error (between-participant).

Kinematic analysis

Figure 5.2 shows the average speed of reaching, the number of movement units, the straightness of reaching, and the dimensionless jerk of reaching as a function of age, vision condition and object size.

Average speed. There was a significant main effect of age ($p < 0.001$) (see Figure 5.2 A). Post-hoc comparisons showed that the average speed in the 1 yr of age phase (M = 26.35 cm/s, SD = 3.28) was significantly higher than all the other age phases. The 6 mo of age phase (M = 18.70 cm/s, SD = 3.23) also had a higher average speed than the reach onset age phase (M = 12.85 cm/s, SD = 3.11). Taken together, the average speed increased from reach onset and continued to increase from 6 mo of age to 1 yr of age.

There was also a significant effect of object size on average movement speed ($p <$ 0.01). Post hoc comparisons showed that the biggest object (2" cube, M = 23.04, SD = 3.39) had a significantly higher average speed than movement for the other objects (1"cube, M = 17.65, SD = 3.40 and pacifier, M = 17.20, SD = 3.34). There was no significant effect of vision on average reach trajectory speed (p = 0.15).

Movement units and straightness. There was a significant main effect of age for the number of movement units ($p < 0.001$) (see Figure 5.2B). Post hoc comparisons showed that the number of movement units in the 1 yr of age phase (M = 2.57, SD = 1.07) was significantly less than all the other age phases. The 6 mo of age phase (M = 3.90, SD = 1.05) also had a fewer movement units than the reach onset age phase (M = 8.00, SD = 1.01).

There was a significant main effect of age for straightness ($p < 0.001$) (see Figure 5.2 C). Post hoc comparisons showed that the onset reach age phase (M = 3.59, SD = 0.63) had a significantly higher straightness ratio than did the other age phases (6mo, M = 1.59, SD = 0.65 and 1yr, M = 1.51, SD = 0.66).

Jerk. There were no significant effects for age, vision condition and object size on mean square jerk In contrast, there was a significant main effect of age for dimensionless jerk (p = .000) (see Figure 5.2 D). Post-hoc comparisons showed that the dimensionless jerk in the 1 yr of age phase (M = 60.53, SD = 95.82) was significantly lower than all the other age phases. The 6 mo of age phase (M = 119.39, SD = 94.14) also had a lower dimensionless jerk than the reach onset age phase (M = 442.17, SD = 91.07).

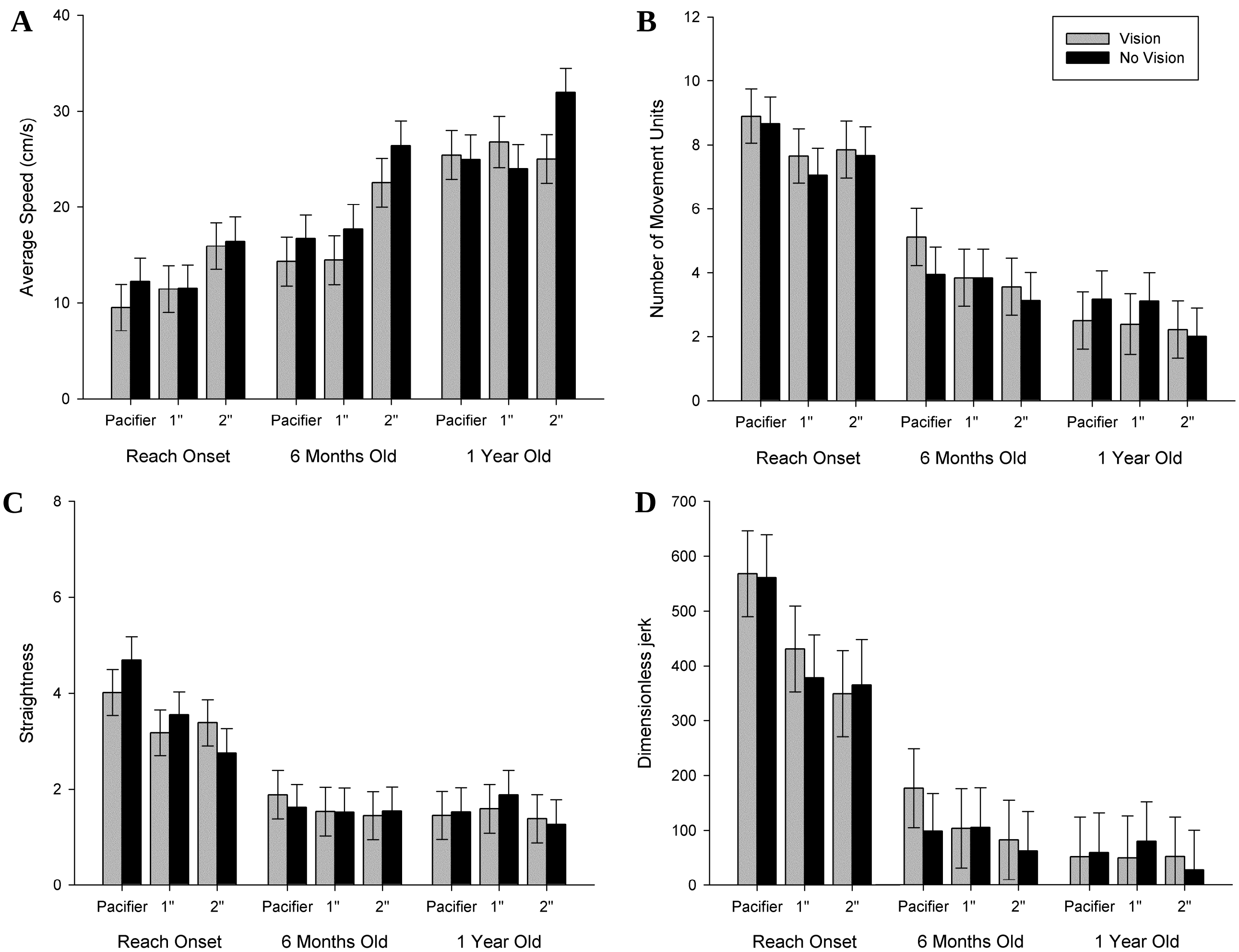

Figure 5. 2. The average speed of reaching (A), the number of movement units (B), the straightness of reaching (C), and the dimensionless jerk (D) of reaching as a function of age, vision condition and object size. Error bars represent one standard error (between-participant).

Discussion

The development of movement acquisition in infancy involves changes in perception and cognition (Adolph, Eppler, & Gibson, 1993; Bertenthal, 1996; E.J. Gibson, 1988). These changes are influenced by the interaction of the organism, task and environmental constraints (Newell, 1986; Savelsbergh, van Hof, Caljouw, Ledebt, & Van der Kamp, 2006). Consistent with this background, the findings of this study showed that visual feedback of the hand and object size influenced the onset of reaching in the development of prehensile movements. The effect of visual feedback of the hand diminished from 6 mo to 1 yr of age, but the effect of object size on how infants reached for the object continued to play a role throughout the first year of life. The results did not support the hypothesis that there are age-related discontinuities in the use of visually guided reaching in infancy (Bushnell, 1985; Berthier & Carrico, 2010). On the contrary, the results showed that the visual feedback of the hand trajectory facilitated the age of reaching onset, but that it did not influence the reaching trajectory movements at 6 mo or 1 yr of age.

The inconsistency in findings on the use of visually guided reaching in infancy may be a consequence of differences in the experimental design and the information that is available in different visual conditions (Berthier & Carrico, 2010; Clifton et al., 1993; Clifton et al., 1994). In contrast to the present study, most visually guided reaching studies in infancy manipulated vision by putting infants in the dark and presenting a luminous or sounding object (Clifton et al., 1993). The challenge is that perception and action are tightly coupled such that the perception action relation is a reciprocal one, a kind of continuous cycle with perception guiding action, and action furnishing new information for perception including about the perceiver, and the environment (E.J Gibson, 1988; Gibson, 1979). Thus, the object in prehension most likely will be perceived differently between light and dark conditions given the significantly different contexts for action.

There is also the possibility that the presented object itself has an effect on how infants move in reaching. In current study, the infants always saw the presented object in both vision and no vision feedback of arm trajectory conditions. Our findings revealed that visual feedback of the hand may not be *necessary* to accomplish the goal of reaching but that it facilitated the onset of the reach component in the development of prehension. These findings also supported the idea that object properties played a more significant role in how infants reached for objects rather the visual feedback of the arm trajectory. That is, the results showed that the object property not only influenced the age of onset reach but also influenced the performance of reaching at reach onset, 6 mo and 1 yr of age.

The experimental findings clearly showed that infants were more likely to reach to the larger object earlier than the small object. This is in line with the findings by the Siddiqui (1995) that younger infants had more difficulty in reaching for the smaller object than the older infants. The significant effect of increasing average movement reach speed to the larger object size reflects a speed–accuracy trade-off (Fitts, 1954). More specifically, the size of the object and the proportion of it to the infant's hand influences prehension (Newell et al., 1993; Newell et al., 1989), and here the significant effect was only observed between the biggest object (2" cube) and small objects (1" cube and pacifier). The difference between the 1" cube and the pacifier was not significant.

These findings are consistent with those of Zaal and Thelen (2005) (1 cm vs. 4 cm in diameter) and Berthier and Carrico's (2010) (1.5 cm vs. 3 cm in diameter) that infants reach movement is faster for big objects when the size is considered relative to the infant's hand size. In contrast, Rocha, Silva, and Tudella (2006) found that the average speed was about the same when objects were relatively big to infants (5 cm vs. 12.5 cm in diameter).

An explanation for why average movement speed increases with age is not straightforward though it is usually interpreted as the consequence of a learned practice effect. The data available that compare the average movement speed in the first year of life show very distinct patterns among studies (Berthier & Carrico, 2010; Berthier & Keen, 2006; Mathew & Cook, 1990; Rocha et al., 2006; Thelen et al., 1993, 1996). The increase in the movement speed shown here from reach onset to 6 mo and 1 yr of age shown here is consistent with the related findings that the reaching movements become straighter and smoother. This supports the proposition that increasing movement speed from reach onset to 6 mo and 1 yr of age reflects the improvement in reaching skill (Rocha et al., 2006).

Berthier and Keen (2006) have identified the kinematic variables (speed/jerk, number of speed peaks/duration, time of peak speed, distance of the reach, and straightness of the reach) that best describe the development of the reach component of prehension in infancy. Overall, there are consistent results across studies in the number of movement units, straightness of reach, and jerk measurement. In the main, the reaching movements from reach onset to 6 mo and 1 yr of age become straighter and smoother (Berthier & Keen, 2006; Carvalho, Tudella, & Savelsbergh, 2007; Mathew & Cook, 1990; Thelen et al., 1993, 1996).

Our analysis of the movement trajectory revealed the importance of using an appropriate jerk measurement, in that we only found a significant main effect of age in dimensionless jerk but not in mean squared jerk. One possible explanation for this is that the mean squared jerk does not necessarily reflect the changes in the smoothness of movement in that it also captures the changes in the absolute values of movement amplitude, speed, and time (Hogan & Sternad, 2009). Therefore, the dimensionless jerk may be a better candidate to measure the smoothness of arm trajectories across different ages.

In summary, the results of this study reveal that visual feedback of the hand trajectory and the size of object influenced the development of prehension. That is, the visual feedback of the hand facilitates the age of reaching onset, but when the reaching movements become sufficiently stable, infants perform equally well with or without visual trajectory feedback of the hand. In contrast, object size consistently affects when and how infants reach for objects. These findings provide further evidence that the influence of visual information on the development of the fundamental movement patterns in infancy is subtle and emerges not from invariant prescriptions for action but as a consequence of the evolving confluence of constraints imposed on action in development (Kugler, Kelso, & Turvey 1982, Newell, 1986).

GENERAL DISCUSSION

The purpose of this dissertation was to examine the characteristics of arm movements that precede the onset of goal-directed reaching movements in infants. Furthermore, we investigated whether the development of prehension is influenced by visual and auditory information feedback and object properties. More specifically, Experiment 1 examined the characteristics of the arm movements that precede the onset of goal-directed reaching movements. Experiment 2 investigated the influence of auditory feedback on the development of reaching movements in infancy. Experiment 3 addressed the question of whether the development of prehension is influenced by visual information of the hand trajectory and object properties. These three studies collectively supported the importance of early exploratory behavior, as well as the dynamical perspective that at a certain developmental time particular constraints may play a role in the emergence and mastery of movement patterns.

Early exploratory behavior

The results of Experiment 1 showed that the characteristics of the goal-directed arm movements that precede the onset of goal-directed reaching movements can be captured by dimensionless jerk. This is the case even though early goal-directed arm movements are seemingly unorganized and difficult to define by changes in frequency and qualitative measures. The finding of a decrease in dimensionless jerk implies that the function of goal-directed arm movements is critical for the emergence of reaching movements. These exploratory movements later facilitate the development of reaching movements.

This finding was also seen in Experiment 2 in which the infants were actively exploring the possibilities for action though little is known about multimodal exploration in the service of guiding reaching and grasping. A central question is what kind of information do infants gain from the exploratory movement and what information elicits further exploration (Adoph, Marin, & Fraisse, 2001). In Experiment 2, the patterns of the goal-directed arm movements were channeled by the presence of concurrent auditory feedback. It was found that infants moved more actively when concurrent auditory feedback of their mother's voice and musical tones was provided. Even though the age of reach onset was the same in the no auditory and the auditory conditions, significantly higher percentages of reaching movements were observed in both auditory conditions (mother's voice and musical tones). Thus, the concurrent auditory information did not accelerate the onset time of reaching, but it did facilitate the exploratory behavior and thereby enhanced the performance of reaching movements. This finding provides further evidence that exploratory arm movements are critical for the development of reaching movements; and also highlight the importance of the perception-action coupling.

In sum, our findings emphasized the importance of early exploratory behaviors. This is in line with the perspective that infants actively explore the possibilities for action in the perception action space (E.J Gibson, 1988). Actions are embedded in a continuous perception-action loop. As they more actively search for the fit between the action and the information available in the environment, the primitive exploratory arm movements subsequently develop into more skillful reaching movements (Thelen & Smith, 1994).

Influence of constraints

Experiments 2 and 3 highlight the importance of visual and auditory information feedback and object properties in the development of reaching in infancy. The auditory feedback facilitated the arm movements that precede reach onset; however, it did not change the age of reaching onset. On the other hand, the visual feedback of the hand trajectory facilitated the age of reaching onset but did not influence reaching performance at 6 months and 1 year of age. Furthermore, the object properties have more influence on the development of reaching in the first year of life. That is, infants were more likely to reach for the bigger object when they started to reach for the object; also, they reached for the larger object with greater speed than they reached for the smaller objects throughout the first year of life.

The findings that the visual feedback of the hand trajectory facilitated the age of reaching onset but not in the auditory feedback conditions could be related to the concept of the fit between perception and action. That is, infants typically can see their arm movements while reaching for the objects. In Experiment 3 the visual feedback of the hand trajectory was blocked in the no vision condition. There is a possibility that the perception action fit was incompatible, therefore, infants would reach for the object at an early age when the visual feedback of the hand trajectory was presented where the perception action fit was connected. On the other hand, the auditory feedback is not presented in the natural setting, although, infants can quickly pick-up the information associated with their own movements but without enhanced practice conditions, the changes observed were only transitory.

Although considerable research has been devoted to understanding the development of perception to the progressions of locomotion (Adolph et al., 1993, Angulo-Kinzler, 2001; Angulo-Kinzler & Horn, 2001; Angulo-Kinzler, Ulrich, & Thelen, 2002; Chen, Fetters, Holt, & Saltzman, 2002), rather less attention has been paid to understanding the development of perception to prehension in infancy. Adolph, Eppler, and E.J. Gibson (1993) found that the perception is action-specific. That is, infants do not learn about slopes in general but rather, they learn about slope specific to their own action. For example, the same infant in a familiar sitting posture avoided risky slopes but in an unfamiliar walking posture, they will try the impossibly risky slopes (Adolph, 1997, 2000).

van der Meer et al., found that even 3 to 5 days-old infants are able to control their hand movements with the vision of their own hand movements. In addition, infants with only 2 weeks of enrichment experience with objects via Velcro-palmed mittens not only spend more time looking at an object but also engage more in object exploration than controls (Needhem, Barrett, & Peterman, 2002). More recent work has shown that compared to the observed group, an active exploring object group spent more time looking at and exploring the object (Libertus & Needham, 2010). All of these findings support the idea that the facilitation of the augmented feedback is only observed when there is a match between the information to be perceived and the performer current action.

These results collectively are consistent with the proposition that the development of movement acquisition is a process of the soft assembly of mutually interacting, multiple-component structures and processes within the perceptual-work space (Newell

& McDonald, 1992). Each component is necessary for the emergence of the movement patterns, but one or more components may have more weight at a certain time (Thelen & Smith, 1996). For example, the visual feedback of the arm trajectory is a critical component that influences the onset of reaching, but later on (at 6 months and 1 year of age) other components factor more in the performance of reaching movements.

All of these components could influence the pattern of reaching movements either concurrently or separately. In Experiment 3, the infants reached earlier for the larger object and when the visual feedback of the arm trajectory was available. At 6 months of age, the object property influenced the reaching patterns, but not the visual feedback of the arm trajectory. However, Berthier and Carrico (2010) have shown that when a precision grasp was required the reaching pattern can be influenced when the visual feedback of the hand was not available. This change in reaching performance based on the object size and relative to the infant's hand size also supports the idea that the developmental course of hand movements is modulated dynamically within the constraints on the action rather than by a prescription for the action (Newell, 1986).

Future directions

The development of prehension reflects the change from early object-oriented arm movements that are composed of a number of submovements to a later phase in which those submovements are blended (von Hosten, 1989; 1990; Wann, 1987; Rohrer et al., 2004). In Experiment 1, the decrease in dimensionless jerk was observed from the early to late object-orientated arm movement phase right before the onset of reaching.

However, further investigation into the submovement decomposition will provide a better understanding of the control process of the movement (Rohrer & Hogan, 2003).

In Experiment 2, changes in the movement amplitude and activity level were observed in the auditory feedback conditions. Future research could also manipulate the quality of the feedback to examine the extent to which this information can be detected and utilized.

As for Experiment 3, it remains to be determined specifically what information in the environment infants pick up to accomplish the goal of reaching, and when they do so. An eye-tracking system may clarify what and when critical information is available in the environment to facilitate the goal of reaching.

Conclusions

Collectively, the results of these experiments allow the following conclusions:

(1) There was a decrease in movement jerk which reflects the increasing ability of infants to adaptively modulate arm movements. This change in the dynamic characteristics of the object-oriented arm movements that precede the onset of goal-directed reaching movements is hypothesised to reflect a critical variable in the developmental process of learning to reach in prehension.

(2) The variable of dimensionless jerk captured the changes in the transition from the early to late phases of object-oriented arm movements. Auditory feedback facilitated the exploratory behavior that precedes the onset of reaching but did not accelerate the onset time of reaching. This finding is consistent with the construct

of affordance that the organism searches for the fit between its action and the information available in the environment.

(3) Visual feedback of the hand and object size influenced the onset of reaching in the development of prehensile movements. The effect of visual feedback of the hand diminished from 6 months to 1 year of age, but the effect of object size on how infants reached for the object continued to play a role throughout the first year of life. These findings provide further evidence that the emergence of movement patterns is a consequence of the evolving confluence of constraints imposed on action in development.

REFERENCES

Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development*, *62*(3, Serial No. 251).

Adolph, K. E. (2000). Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science, 11*, 290-295.

Adolph, K. E., & Berger, S. E. (2005). Physical and motor development. In M. H. Bornstein & M. E. Lamb (Eds.), *Developmental science: An advanced textbook*, pp. 223-281. Hillsdale, NJ: Erlbaum.

Adolph, K. E., & Berger, S. A. (2006). Motor development. In W. Damon & R. Lerner (Series Eds.) & D. Kuhn & R. S. Siegler (Vol. Eds.), *Handbook of child psychology: Vol 2: Cognition, perception, and language*, pp. 161-213. (6th ed.) New York: Wiley.

Adolph, K. E., Eppler, M. A., & Gibson, E. J. (1993). Crawling versus walking infants' perception of affordances for locomotion over sloping surfaces. *Child Development: Special Issue on Biodynamics, 64*, 1158-1174.

Adolph, K. E., Marin, L. M., & Fraisse, F. E. (2001). Learning and exploration: Lessons from infants. Commentary on Stoffregen and Bardy. *Behavioral and Brain Sciences*, *24*, 213–214.

Adolph, K. E., Vereijken, B., & Shrout, P. E. (2003). What changes in infant walking and why. *Child Development*, *74*, 475-497.

Angulo-Kinzler, R. M. (2001). Exploration and selection of intralimb coordination patterns in 3-month-old infants. *Journal of Motor Behavior*, *33*, 363–376.

Angulo-Kinzler, R. M., & Horn, C. L. (2001). Selection and memory of a lower limb motor-perceptual task in 3-month- old infants. *Infant Behavior and Development*, *24*, 239 – 257.

Angulo-Kinzler, R. M., Ulrich, B., & Thelen, E. (2002). Three-month-old infants can select specific leg motor solutions. *Motor Control*, *6*, 52–68.

Bernstein, N. (1967). *Co-ordination and regulation of movements*. New York: Pergamon.

Bertenthal, B. (1996). Origins and early development of perception, action, and representation. *Annual Review of Psychology*, *47*, 431-459.

Berthier, N. E., & Carrico, R.L. (2010). Visual information and object size in infant reaching. *Infant Behavior and Development*, *33*, 555-566.

Berthier, N. E., & Keen, R. (2006). Development of reaching in infancy. *Experimental Brain Research*, *169*, 507-518.

Bhat, A. N., Heathcoch, J. C., & Galloway, J. C. C. (2005). Toy-oriented changes in hand and joint kinematics during the emergence of purposeful reaching. *Infant Behavior and Development*, *28*, 445-465.

Bhat, A. N., & Galloway, J. C. (2006). Toy-oriented changes during early arm movements: hand kinematics. *Infant Behavior and Development*, *29*, 358-72.

Bower., T.G.R. (1972). Object perception in infants. *Perception*, *1*, 15-30.

Brandt, I. (1980). Postnatal growth of preterm and full-term infants. In F. E. Johnston, A. F. Roche, & C. Susanne (Eds.), *Human physical growth and maturation*, pp,139-159. New York: Plenum Press.

Bushnell, E. W. (1985). The decline of visually guided reaching during infancy. *Infant Behavior and Development, 8,* 139-155.

Carrico, R.L., & Berthier, N. E. (2008). Vision and precision reaching in 15 month old infants. *Infant Behavior and Development, 31,* 62-70.

Carvalho, R. P., Tudella, E., & Savelsbergh, G. J. P. (2007). Spatio-temporal parameters in infant's reaching movements are influenced by body orientation. *Infant Behavior and Development*, *30*, 26-35.

Cesari, P., & Newell, K. M. (2000a). The body scaling of grip configurations in children aged 6–12 years. *Developmental Psychobiology, 36,* 301–310.

Cesari, P., & Newell, K. M. (2000b). Body scaled transitions in human grip configurations. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1657–1668.

Chen, Y. P., Fetters, L., Holt, K. G., & Saltzman, E. (2002). Making the mobile move: constraining task and environment. *Infant Behavior and Development*, *25,* 195–220.

Clifton, R. K., Muir, D. W., Ashmead, D. H., & Clarkson, M. G. (1993). Is visually guided reaching in early infancy a myth? *Child Development*, *64,* 1099-1110.

Clifton, R. K., Perris, E. E., & Bullinger, A. (1991). Infants' perception of auditory space. *Developmental Psychology, 27,* 187-197.

Clifton, R. K., Rochat, P., Robin, D. J., & Berthier, N. E. (1994). Multimodal perception in the control of infant reaching. *Journal of Experimental Psychology: Human Perception and Performance*, *20,* 876-886.

Corbetta, D., & Thelen. E. (1995). A method for identifying the initiation of reaching movements in natural prehension. *Journal of Motor Behavior, 27*, 285-293.

Darcheville, J., Boyer, C., & Miossec, Y. (2004). Training infant reaching using mother's voice as reinforcer. *European Journal of Behavior Analysis 5,* 43-51.

DeCasper, A. J., & Fifer, W. P. (1980). Of human bonding: Newborns prefer their mothers' voices. *Science*, *208*, *1174-1176*.

Dibiasi, J., & Einspieler, C. (2002). Can spontaneous movements be modulated by visual and acoustic stimulation in 3-month-old infants? *Early human development*, *68,* 27-37.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*, 381–391.

Fowler, C. A., & Turvey, M. T. (1978). Skill acquisition: An event approach with special reference to searching for the optimum of a function of several variables. In G. Stelmach (Ed.), *Information processing in motor learning and control.* New York: Academic Press.

Gesell, A. (1929). Maturation and infant behavior pattern. *Psychological Review, 36*, 307–319.

Gesell, A. & Ames, L. (1947). The infant's reaction to this mirror image. *The Journal of Genetic Psychology, 70*, 141-154.

Gibson, E.J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology, 39,* 1-41.

Gibson, E. J. (1991). *Odyssey in learning and perception*. Cambridge, MA: MIT Press.

Gibson, E.J. (1997). An ecological psychologist's prolegomena for perceptual development: A functional approach. In C. Dent-Read and P. Zukow-Goldring (Eds.), *Evolving explanations of development*, pp. 23 - 54. Washington, DC: American Psychological Association.

Gibson, E. J. (2000). Perceptual learning in development: some basic concepts. *Ecological Psychology, 12,* 295–302.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton-Mifflin.

Halverson, H. M. (1931). An experimental study of prehension in infants by means of systematic cinema records. *Genetic Psychology Monographs, 10,* 107-283.

Hein, A., & Held, R. (1967). Dissociation of the visual placing response into elicited and guided components. *Science*, *158*, 390-392.

Hogan, N. (1984). An organizing principle for a class of voluntary movements. *The Journal of Neuroscience, 4,* 2745- 2754.

Hogan, N., & Flash, T. (1987). Moving gracefully: Quantitative theories of motor coordination. *Trends Neuroscience, 10,* 170-174.

Hogan, N., & Sternad, D. (2009). Sensitivity of smoothness measures to movement duration, amplitude, and arrests. *Journal of Motor Behavior*, *41*, 529-534.

Humphrey, T. (1969). Postnatal repetition of human prenatal activity sequences with some suggestions of their neuroanatomical basis. In R. Robinson (Ed.), *Brain and early behavior*. New York: Academic Press.

Jones L.A., Lederman S.J. (2006). *Human hand function*. New York: Oxford UP.

Kawai, M., Savelsbergh, G. J., & Wimmers, R. H. (1999). Newborns spontaneous arm movements are influenced by the environment. *Early Human Development, 54*, 15-27.

Konczak, J., Borutta. M., & Dichgans, J. (1995). The development of goal-directed reaching in infants: hand trajectory formation and joint torque control. *Experimental Brain Research, 106,* 156-68.

Konczak, J., & Dichgans, J. (1997). The development toward stereotypic arm kinematics during reaching in the first 3 years of life. *Experimental Brain Research, 117,* 346-354.

Konczak, J., & Dichgans, J. (1997). The development of hand trajectory formation and joint kinematics during reaching in infancy. In M. Fetter., T. Haslwanter & H. Misslich (Eds.), *Three-dimensional kinematics of eye, head and limb movements.* (pp. 313-318).

Kugler, P. N., Kelso, J. A. 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. 5–78). New York: Wiley.

Kugler, P. N. (1986). A morphological perspective on the origin and evolution of movement patterns. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 459–525). Dordrecht, The Netherlands: Martinus Nijhoff.

Lagerspetz, K., Nygard, M., and Strandvik, C. (1971). The effects of training in crawling on the motor and mental development of infants. *Scandinavian Journal of Psychology, 12*, 192-197.

Lasky R. E. (1977). The effect of visual feedback of the hand on the reaching and retrieval behavior of young infants. *Child Development, 48*, 112,-117.

Lee, H. -M., Bhat, A., Scholz, J. P., & Galloway, J. C. (2008). Toy-oriented changes during early arm movements IV : Shoulder – elbow coordination. *Infant Behavior and Development, 31*, 447-469.

Lee, M., Liu, Y., & Newell, K. M. (2006). Longitudinal expressions of infant's prehension as a function of object properties. *Infant Behavior and Development, 29*, 481-493.

Libertus, K., & Needham, A. (2010). Teach to reach: The effects of active versus passive reaching experiences on action and perception. *Vision Research, 50*, 2750-2757.

Littell R. C., Milliken G. A., Stroup W. W., Wolfinger R. D., & Schabenberger O. *(2006). SAS for mixed models*. 2nd ed. Cary, NC: SAS Institute.

Mathew, A., & Cook, M. (1990). The control of reaching movements by young infants. *Child Development, 61*, 1238-1257.

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

McGraw, M. B. (1943). *The neuromuscular maturation of the human infant*. New York: Columbia University Press.

McGraw, M. B., & Breeze, K. W. (1941). Quantitative studies in the development of erect locomotion. *Child Development, 12*, 267-303.

Myowa-Yamakoshi, M., & Takeshita, H. (2006). Do huma fetuses anticipate self-oriented actions? A study by four-dimensional (4D) ultrasonography. *Infancy, 10*, 289-301.

Napier, J. (1980). *Hands*. New York: Pantheon.

Needham, A., Barrett, T., & Peterman, K. (2002). A pick-me-up for infants' exploratory skills: Early simulated experiences reaching for objects using 'sticky mittens' enhances young infants' object exploration skills. *Infant Behavior and Development*, *25*, 279-295.

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: Martinus Nijhoff.

Newell, K. M. (1996). Change in movement and skill: Learning, retention, and transfer. In M. Latash & M. T. Turvey (Eds.), *Dexterity and its development.* Hillsdale, NJ: Erlbaum.

Newell, K. M., Liu, Y.-T., & Mayer-Kress, G. (2003). A dynamical systems interpretation of epigenetic landscapes for infant motor development. *Infant Behavior and Development*, *26*, 449–472.

Newell, K. M., & McDonald, P.V. (1992). Practice: A search for task solutions. In R. Christina & H.M. Eckert (Eds.), *American Academy of Physical Education papers: Enhancing human performance in sport: New concepts and developments* (pp. 51-60). Champaign, IL: Human Kinetics.

Newell, K. M., McDonald, P. V., & Baillargeon, R. (1993). Body scale and infant grip configurations. *Developmental Psychobiology*, *26*, 195–206.

Newell, K. M., Scully, D. M., McDonald, P. V., & Baillargeon, R. (1989). Task constraints and infant grip configurations. *Developmental Psychobiology, 22*, 817–832.

Newell, K. M., Scully, D.M., Tenenbaum, F., & Hardiman, S. (1989). Body scale and the development of prehension. *Developmental Psychobiology, 22*, 1–13.

Pavlov, I. P. (1927). *Conditioned reflexes* (G. V. Anrep, Trans.). London: Oxford University Press.

Piaget, J. (1952). *The origins of intelligence in children*. New York: International Universities Press.

Piek, J. P., & Carman, R. (1994). Developmental profiles of spontaneous movements in infants. *Early Human Development*, *39*, 109-126.

Platz, T., Denzler, P., Kaden, B., & Mauritz, K.-H. (1994). Motor learning after recovery from hemiparesis. *Neuropsychologia, 32*, 1209-1223.

Rocha, N. A. C. F., Silva, F. P.S., & Tudella, E. (2006). The impact of object size and rigidity on infant reaching. *Infant Behavior and Development*, *29*, 251-61.

Rohrer, B., Fasoli, S., Krebs, H. I., Hughes, R., Volpe, B., Frontera, W. R., et al. (2002). Movement smoothness changes during stroke recovery. *Journal of Neuroscience, 22*, 8297– 8304.

Rovee-Collier, C. K., & Capatides, J. B. (1979). Positive behavioral contrast in 3-month-old infants on multiple conjugate reinforcement schedules. *Journal of the Experimental Analysis of Behavior*, *32*, 15-27.

Rovee-Collier, C. K., & Gekoski, M. J. (1979). The economics of infancy: a review of conjugate reinforcement. *Advances in Child Development and Behavior*, *13*, 195–255.

Prechtl, H. F. R. (1990). Qualitative changes of spontaneous movements in fetus and preterm infant are a marker of neurological dysfunction. *Early Human Development 23*, 151–158.

Prechtl, H. (1997). State of the art of a new functional assessment of the young nervous system. An early predictor of cerebral palsy. *Early Human Development*, *50*, 1-11.

Robbins, W. J., Brody, S., Hogan, A. G., Jackson, C. M., & Greene, C. W. (1928). *Growth*. New Haven: Yale University Press.

Rohrer, B., Fasoli, S., Krebs, H. I., Hughes, R., Volpe, B., Frontera, W. R., et al. (2002). Movement smoothness changes during stroke recovery. *Journal of Neuroscience, 22*, 8297– 8304.

Rohrer, B., Fasoli, S., Krebs, H. I., Volpe, B., Frontera, W. R., Stein, J., et al. (2004). Submovements grow larger, fewer, and more blended during stroke recovery. *Motor Control*, *8*, 472-83.

Savelsbergh, G. J. P., & van der Kamp, J. (1994). The effect of body orientation to gravity on early infant reaching. *Journal of Experimental Child Psychology, 58*, 510-528.

Savelsbergh, G. J. P., van Hof, P., Caljouw, S. R., Ledebt, A. & Van der Kamp, J. (2006). No single factor has priority in action development. *Journal of*

Integrative Neuroscience, 5, 493-504.

Schaal, S., & Sternad, D., Osu, R., & Kawato, M. (2004). Rhythmic arm movement is not discrete. *Nature Neuroscience, 7,* 1136-1143.

Shirley, M. M. (1931*). The first two years: A study of twenty-five babies, Vol. I. Locomotor development*. Minneapolis: The University of Minnesota Press.

Shuttleworth, F. K. (1949). The adolescent period: A graphic atlas. *Monographs of the Society for Research in Child Development, 14*.

Skinner, B. F. (1953). Science and human behavior. New York: Macmillan.

Siddiqui, A. (1995). Object size as a determinant of grasping in infancy. *Journal of Genetic Psychology, 156*, 345–358.

Siqueland, E. R., & DeLucia, C. A. (1969). Visual reinforcement of nonnutritive sucking in human infants. *Science, 165*, 1144 –1146.

Smith, M. A., Brandt, J., & Shadmehr, R. (2000). Motor disorder in Huntington's Disease begins as a dysfunction in error feedback control. *Nature, 403*, 544-549.

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

Thelen, E. (1979). Rhythmical stereotypies in normal human infants. *Animal Behavior, 27*, 699-715.

Thelen, E. (1980). Determinants of amounts of stereotyped behavior in normal human infants. *Ethology and Sociobiology, 1*, 141-150.

Thelen, E. (1981). Rhythmical behavior in infancy: An ethological perspective. *Developmental Psychology, 17*, 237-257.

Thelen, E. (1983). Learning to walk is still an "old" problem: a reply to Zelazo. *Journal of Motor Behavior*, *15*, 139-161.

Thelen, E. (1989). Self-organization in developmental processes: Can systems approaches work? In M. Gunnar & E. Thelen (Eds.), *Systems in development: The Minnesota Symposia in Child Psychology* (Vol. 22, pp. 77-117). Hillsdale, NJ: Erlbaum.

Thelen, E. (1990). Coupling perception and action in the development of skill: A dynamic approach. In H. Bloch & B. Bertenthal (Eds.), *Sensory-motor organization and development in infancy and early childhood* (pp. 39–56). Dordrecht: Kluwer.

Thelen, E. (1994). Three-month-old infants can learn task-specific patterns of interlimb coordination. *Psychological Science, 5*, 280-285.

Thelen, E. (1995). Motor development: A new synthesis. *American Psychologist*, *50*, 79-95.

Thelen, E., Corbetta, D. & Spencer, J. P. (1996). Development of reaching during the first year: role of movement speed. *Journal of Experimental Psychology: Human Perception Performance, 22*, 1059–1076.

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*, 1058-1098.

Thelen, E., & Fisher, D. M. (1983). From spontaneous to instrumental behavior:

Kinematic analysis of movement changes during very early learning. *Child Development*, *54*, 129-140.

Thelen, E., Fisher, D. M. & Ridley-Johnson, R. (1984). The relationship between physical growth and a newborn reflex. *Infant Behavior and Development, 7,* 479-493.

Thelen, E., Fisher, D. M., Ridley-Johnson, R., & Griffin, N. J. (1982). The effects of body build and arousal on newborn infant stepping. *Developmental Psychobiology*, *15*, 447-453.

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

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of perception and action*. MIT Press.

Trevarthen, C. (1984). How control of movement develops. In H. T. A. Whiting (Ed.), *Human motor actions: Bernstein reassessed* (pp. 223–261). Amsterdam: North Holland.

Turvey, M. T. & Fitzpatrick, P., (1993). Commentary: development of perception-action systems and general principles of pattern formation. *Child Development, 64*, 1175–1190.

van der Fits, I. B. M., Otten, E., Klip, A. W. J., van Eykern, L. A., & Hadders-Algra, M. (1999). The development of postural adjustments during reaching in 6- to 18-month-old infants. *Experimental Brain Research, 126,* 517-528.

van der Meer, A., van der Weel, R. & Lee, D. (1995). The functional significance of arm movements in neonates. *Science, 267*, 693-695.

von Hofsten, C. (1982). Eye-Hand coordination in the newborn. *Developmental Psychology, 18*, 450-461.

von Hofsten, C. (1991). Structure of early reaching movements: A longitudinal study. *Journal of Motor Behavior, 23*, 280–292.

von Hofsten, C. (1993). Prospective control: A basic aspect of action development. *Human Development, 36*, 253-270.

von Hofsten, C., & Ronnqvist, L. (1993). The structuring of neonatal arm movements. *Child Development, 64*, 1046–1057.

Visser, H. K. A. (1966). Growth in early infancy. In J. J. van derWerff ten Bosch&A. Haack (Eds.), *Somatic growth of the child*. Springfield, IL: Charles C. Thomas.

Waddington, C. H. (1957). *The strategy of the genes*. London: George Unwin & Unwin.

Wann. J.P., (1987). Trends in the refinement and optimization of fine-motor trajectories: Observations from an analysis of the handwriting of primary school children. *Journal of Motor Behavior 19*, 13-37.

Warren, W. H. (1984). Perceiving affordances: visual guidance of stair climbing. *Perception, 10*, 683-703.

Whyte, V. A., McDonald, P.V., Baillargeon, R, & Newell, K.M. (1994). Mouthing and grasping of objects by young infants. *Ecological Psychology, 6, 205-218.*

Wolff, P. H. (1967). The role of biological rhythms in psychological development. *Bulletin of the Menninger Clinic, 31*, 197–218.

Wolff, P. H. (1968). Stereotypic behavior and development. *Canadian Psychologist 9*, 474–83.

Zaal, F. T., & Thelen, E. (2005). The developmental roots of the speed– accuracy trade-off. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 1266–1273.

Zelazo, P. R., Zelazo, N. A., & Kolb, S. (1972a). Walking in the newborn. *Science, 176*, 314–315.

Zelazo, P. R., Zelazo, N. A., & Kolb, S. (1972b). Newborn walking. *Science, 117*, 1058–1059.

Zoia, S., Blason, L., D'Ottavio, G., Bulgheroni, M., Pezzetta, E., Scabar, A., et al. (2007). Evidence of early development of action planning in the human foetus: a kinematic study. *Experimental Brain Research, 176*, 217-226.

VITAE

Mei-Hua Lee

Education

2011	Ph.D. Kinesiology The Pennsylvania State University
2005	M.S. Physical Education National Taiwan Normal University Taiwan
2002	B.E. Physical Education National Taiwan Normal University Taiwan

Peer-Reviewed Publications

Lee, M-H., Ranganathan, R., & Newell, K. M. (in press). Changes in Object-oriented Arm Movements that Precede the Transition to Goal-Directed Reaching in Infancy. *Developmental Psychobiology*.

Ranganathan, R., **Lee, M-H**., Brown, A. J., & Newell, K. M. (in press). Grasping possibilities for action: influence of object function and action capabilities on grasp facilitation. *Human Movement Science*.

Lee, M-H, Bodfish, J. W., Lewis, M. H., & Newell K. M. (2010). Low dimensional temporal organization of spontaneous eye blinks in adults with developmental disabilities and stereotyped movement disorder. *Research in Developmental Disabilities, 31*, 250-255.

Hong, S.L., **Lee, M-H**., & Newell, K.M. (2007). Magnitude and structure of force variability: mechanical and neurophysiological influences. *Motor Control, 11*, 119-135.

Lee, M-H., Liu, Y-T., & Newell, K. M. (2006). Longitudinal expressions of infant's prehension as a function of object properties. *Infant Behavior and Development, 29*, 481–493.