The Syntax of Human Infant Reaching

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Early infant reaching is composed of multiple hand accelerations representing a sequence of corrective submovements. At the developmental onset of reaching, infants appear to "wrestle" their hands to a target and only very gradually show smoothing of their movements with experience. This rough character of infant reaching likely reflects the lack of development of the cerebellum. Cerebral cortical systems are able to provide approximate solutions for reaching tasks, and with extended experience they become better at generating accurate initial movements. The improvement in generating initial movements is at least partly due to improved mapping of the initial conditions of the body, environment, and task to the initial movement. Data from infants show that it is only after 8 months of practice that a primary movement comes to dominate the reach as they do in older children and adults.

Thus, the syntax of early reaching is similar to the syntax of mature reaching. This early syntax allows infants to accomplish their goal of obtaining objects in the world. Development occurs in a manner that allows for skill optimization [22]. Infant reaching uses neural systems that provide the basis of adult reaching.

1 Introduction

Adults are skilled at using their arms to accomplish tasks in the world. Generally, we move in complex ways to accomplish goals through sequences of movements. Reaching movements are corrected and adapted on both short- and long-time scales. In the short term, single reaches are corrected to bring the hand to the target, and in the long term, experience over days and weeks provides the basis for gradual improvement in the quality of reaching. The way in which reaching movements are sequenced is implicitly rule-governed, and these rules comprise a

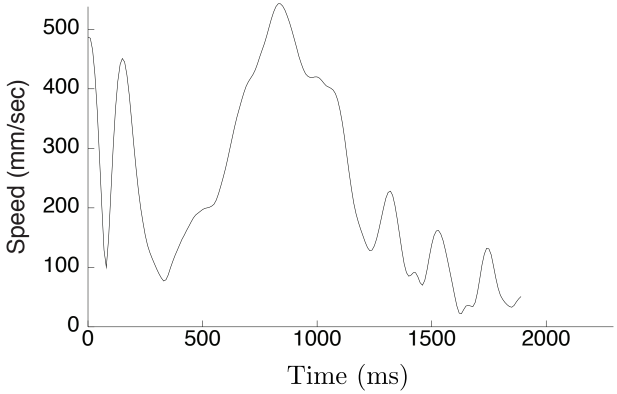

Figure 1: Hand speed profile of a 7-month-old infant reaching for a small toy (from [8]). The minima in the hand-speed profile indicate a change from a period of deceleration to accceleration and define a von Hofsten "movement unit." [32,33]

syntax of reaching in the same way that sequencing of words defines the syntax of language.

The syntactic complexity of adult movement as studied in the laboratory is limited because experimental procedures are highly simplified. In contrast, studies of infant reaching are usually more ecologically valid because restrictive experimental control of infants is not possible. Infant reaching is much less "controlled" than adult reaching in that typical reaches show a sequence of hand accelerations and decelerations that presumably reflect a sequence elementary submovements (e.g., Figure 1). This pattern of hand acceleration and deceleration provides insight into how movement is composed at this ontogenetic stage. It should be emphasized that this pattern is the result of the infant's response to the constraints of the task and not a consequence of power limitations of the motor system as infants are capable of rapid and large amplitude arm movements [4]. Because further development is built upon this early reaching pattern, understanding the syntax of infant reaching provides insight into older children's and adult's reaching.

The plan of this paper is the describe development of infant reaching over the first two years and then consider how the behavioral syntax might be related to current theories of motor control.

2 Syntax of infant reaching

At birth, human infants are capable of visually orienting to laterally placed sounds and of making directed hand movements toward visual targets. These "pre-reaching" movements are not successful in making contact with targets, but are visually directed in that infants show more reaches to the hemifield in which a target appears [16, 35]. Soon after birth infants move their arms against loads in order to maintain sight of the hand [31, 30].

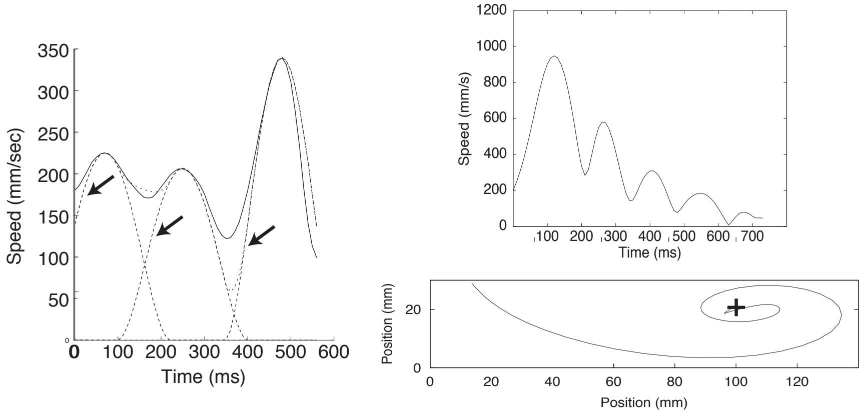

Figure 2: Left: Hand-speed profile of 6-month-old infant reaching for a small, hand-sized toy (Adapted from [4]) The movement has been decomposed into the sum of three bell-shaped velocity profiles (arrows) suggesting that the movement was composed of three submovements. Right: Hand-speed profile (top) and x-y position (bottom) of a reaching movement of a 16-week-old infant (adapted from [6]). This movement is a underdampened movement about the endpoint (lower panel, cross).

Reaching that results in successful contact with targets appears around 15 weeks-of-age [6, 32, 33]. Originally, this behavior was called visually-guided reaching, but it is more properly called visually-elicited reaching. Visually-guided reaching refers to the use of vision of the hand as a way to estimate hand position during reaching [10]. However, it is now clear that infants focus their visual attention on the target and do not view the hand during reaching. Reaching is unaffected by removal of vision of the hand at this age [5, 13, 14].

Thus, early reaching is based on vision of the target and on proprioceptive signals from the arm. Later, towards the end of the first year of life, children acquire the ability to independently move their fingers, and vision of the hand gains importance in the configuring and orienting of the hand in anticipation of contact with target objects [5].

The topography of infant reaching is different from adults in that in the latter simple reaches are generally made using a single motor command with inflight corrective movements as needed [18, 17, 21]. In contrast, the jerky reaching movements of infants reflects a sequence of corrected submovements (e.g., Figures 1 and 2 left). Von Hofsten [34, 35] was the first to label these elemental movements as “movement units.” Thelen et al. [29] argued against this conclusion and suggested that the accelerations were the result of the musculoskeletal arm dynamics.

Careful examination of the kinematics of reaching of very young infants supports the hypothesis that some of the hand accelerations are due to the mechanical dynamics of the arm. Berthier et al. [6] observed that single reaching

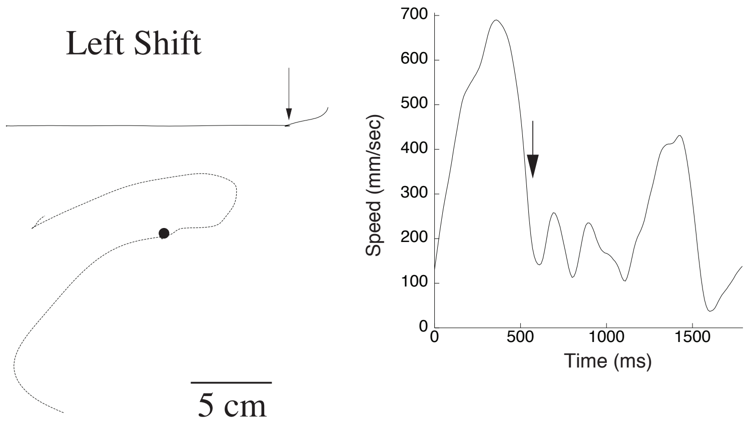

Figure 3: Left: Top view of 7-month-old infant reaching to a shifting target. The top line shows the position of the target at the beginning of the reach (down arrow) and during a shift to the left. The trace below shows the positions of the hand during the reach. The solid dot shows the position of the hand at the time the target started to shift to the left. Right: Hand-speed profile of the reach on the left. The down arrow shows the time at which the target started shifting to the left. Note the large acceleration of the hand indicating a corrective movement to the left. (adapted from [8]).

movements in very young infants showed the features of underdampened oscillations around the end point thus suggesting that at least some of the movement units of the reach are the result of arm dynamics and not the result of individual movement commands (Figure 2, right). Berthier et al. [9] used a four degree-of-freedom model of the infant's arm to show that these kinematic profiles could result from simple shifts in equilibrium potential.

But infant reaches are not simply composed of a single shift in equilibrium point. Berthier and Robin [8] presented 7-month-olds with a target that unpredictably shifted during midreach. Figure 3 shows of an overhead view of one reach where a target shifts to the left in midreach and the infant responds by shifting the hand to the left. Analysis across trials suggested that the latency of response to shift of a target was between 250 and 400 ms.

Thus, the sequence of accelerations observed in young infant reaching reflects a mix of motor commands and mechanical oscillations. Absent the availability of techniques to actually record individual motor commands, the source of a particular acceleration is uncertain. Whatever the case, the magnitudes of the sudden changes in the hand-speed profile decrease with age and it is likely that beyond early infancy the primary cause of the acceleration changes is the application of a new motor command by the descending motor system.

The second feature of the syntax of infant reaching is the fact that early

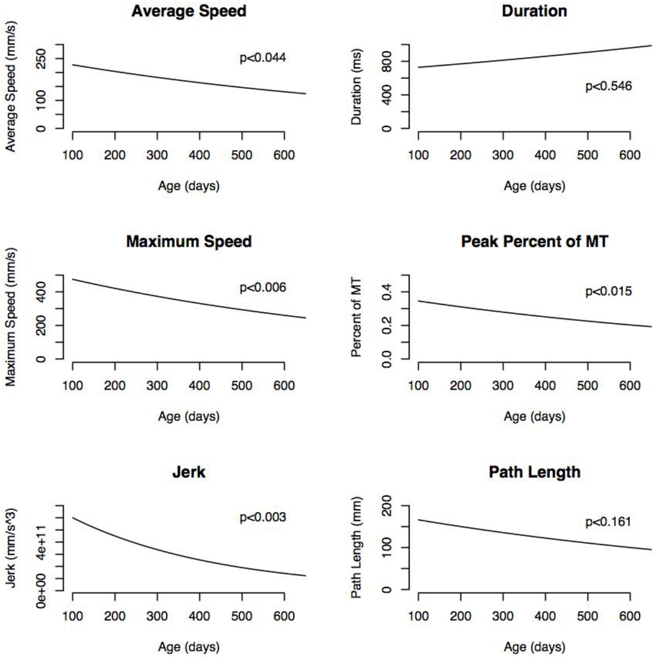

Figure 4: Kinematic change over the first two years of life (from [7]). These are exponential, mixed effects fits of longitudinal data over the firs two years of life. The overall trend with age is towards slower, less jerky movements with age.

movements show a "proximodistal structure." That is, movement of the hand to the target is accomplished by use of the proximal musculature, the trunk and shoulder, with the distal degrees of freedom locked [6]. This feature is probably a joint consequence of the maturational progression of development from the proximal to distal musculature, and to the fact that the main task faced by the young infant is to move the hand to the target and later accommodate the grip to the feel of the target itself.

Lastly, the main trend in the development of reaching over the first two years of life is a slow improvement in reach smoothness (Figure 4) [7]. The speed of reaching actually decreases with age and is accompanied by a decrease in the jerk of reaching.

3 Neural processing modules

The cerebral cortex, basal ganglia, and cerebellum work in parallel to generate and control reaching movements. Often, we focus on the role of particular brain regions in supporting tasks, but it is clear that the connections between regions play an important role in generating action [19, 22, 27, 28]. Of particular interest is the Houk's theory [22] of distributed processing modules that hypothesizes that parallel subcortical loops through the basal ganglia and cerebellum control reaching movements. The loops through the basal ganglia are posited to be involved in action selection and correction and to use reinforcement learning, while the loops through the cerebellum are described as being involved in action refinement and using supervised learning [22].

Historically, researchers interested in brain development of young children have thought of the problem in maturational terms. In this context, maturation connotes both preordained, genetically-controlled development and the notion that particular abilities depend on the maturation of a particular area of the brain [15, 24, 25]. For example, the rapid development of executive function observed around the age of three years was said to depend on the maturation of prefrontal cortex, as if the prefrontal cortex were nonfunctional before three. However, this view has the drawback that prefrontal cortex develops from birth through young adulthood and executive function changes during this entire time span.

As an alternative, Mark Johnson has suggested the we think of neural development as an interactive specialization [24, 25]. In this view, the development a neural center depends on its interaction with other centers through developing connections. This view focuses attention on the development of broader patterns of connections among brain regions as opposed to the more local consideration of the maturational view. This view is highly compatible with the modern focus on primary role that loops between the cortex, basal ganglia, and cerebellum play in the generation of action.

While the development of MRI, fMRI, and other techniques has greatly improved our knowledge about how the brain initiates and controls action in humans, our knowledge of the functional capacity of the various neural systems in human infancy is limited. The development of the major systems involved in controlling action, the cerebral cortex, basal ganglia, cerebellum, and the descending motor system, are only sketchily understood. We know that the cerebral cortex develops extensively through childhood and early adulthood with a period of early synaptogenesis and pruning over the first years of life [23] and with further development of the grey and white matter into late adolescence [20]. The basal ganglia appear to be more developed at birth [2, 3], but clearly the developments of basal ganglia-cortical loops would depend on the development of the overlying cortex.

The development of the cerebellum has been well studied in humans, largely because of the presence of the external granular layer, which is the proliferative zone for the granule cells of the cerebellum. In contrast to almost all other areas of the human brain, the granule cells are largely generated after birth in humans. In the first months after birth the granule cells migrate internally to form the granular layer of the mature cortex. Migration of the granule cells is completed by the first birthday in humans [1].

In this context of neural development, the infant is generating directed arm movements at birth, making reliable contact with objects at about 15 weeks-of-age, and showing considerable improvement in their reaching skill by the first birthday. How can we begin to think of how this might occur? Johnson's discussion [25] of interactive specialization as underlying brain development proposes that genetic expression interacts with brain function and behavior to drive change, that interaction through brain networks results in specialization of brain areas, that the process is self-organizing and activity dependent, and that the mapping between neural activity and behavior is dynamic and changes with age.

How might the data from infant reaching inform us about the development of Houk's distributed processing modules? First, given the rudimentary state of cerebellar cortex at birth and through a major portion of the first year, the influence of the cerebellar loops should be limited. Thus, at 15 weeks-of-age reaching should largely be under the control of the basal ganglia—cerebral cortex loops. These loops select a rough action that might need correction during execution. In adults, these actions would be refined through the action of the cerebellar loops, but this polishing of the movement should be limited in young infants given their limited development of the cerebellum.

With repeated experience the basal ganglia loops become better at selecting actions for particular contexts using reinforcement learning. Reinforcement learning suffers from the curse of dimensionality, but in early infancy two aspects of the situation make it tractable. First, infants use cocontraction of the distal musculature to reduce the dimensionality of movement [6]. Second, the infant's workspace is considerably smaller than adults. Their arms are considerably shorter than adults and the functional length of the arm is further reduced by the elbow flexed posture infants typically employ. Berthier, Rosenstein, and Barto [9] showed using simulations of a dynamic arm that reinforcement learning is possible in this situation.

It is surprising that infant reaches show this jerky character for so long. For example, the reach displayed in Figure 1 is from a 7-month-old, a child that has had at least three months of practice in reaching. However, the task faced by the basal ganglia—cortical loops is formidable. During this early period infants are growing at the fastest rate of their lives and the lengths and masses of their arms are changing rapidly. Presumably, this requires constant recalibration of the context-selection mapping instantiated by the basal ganglia loops, and this occurs with minimal input from the cerebellar loops. This period of development may be an example of interactive specialization [25] in that in early development the loops respond broadly and result in selection from a relatively general set of possible actions. Later, the loops respond more selectively and selection is from a more restricted, specific set. The early broad selection may be necessary to accommodate to the possible large changes that might occur in the infant's body and environment.

As time passes during the first year and the cerebellar network becomes more mature, the cerebellar—cortical loops should gradually exert influence on the approximate commands selected by the basal ganglia loops. We note that reaching maintains its jerky character well through the first year of life, it is only during the second year that movement becomes smoother and composed of a primary movement with one or two corrections. This kinematic development is predicted by the very slow development of the cerebellum.

4 Conclusions

Studies of development offer opportunities and challenges that are not present in other populations. Our work with the development of human infant reaching offers an opportunity to study the protracted development of a skill. It also presents an opportunity to study the control of movement in a system that is simplified as compared to the skilled actions of adults. Studies of human infants who have temporary limitations (e.g., cataracts [26], limb casting [11, 12], etc.) also allow for the study of the role of experience in the development of behavior.

Infant reaches appear very different from adult reaches when studied on videotape or with sophisticated instruments. Their primary difference is that infants reach with a sequence of several elementary movements that are corrected to bring the hand to the target. These reaches become functionally effective at about 4 months-of-age. The rules by which these movements are sequenced is implied by the mappings encoded by the basal ganglia—cortical loops. The primary metric that is used to select actions is one of function, does the action bring the hand to the target in a timely way with minimal effort and maximal safety? This metric depends on a body that is changing on a daily basis and thus, reinforcement learning using crude signals of success and efficiency is an appropriate way to select actions on a daily basis.

As the infant enters the second year-of-life reaching actions become smoother because of the increasing influence of the cerebellar loops. However, it will require several more months before the sequence of movements underlying reaching in infants approaches the smoother reaches of adults where a single action can be chosen to accomplish a task that may or may not require correction.

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