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Postural Control During Reaching in Young Infants: A Dynamic Systems Approach

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THELEN, E. AND J.P. SPENCER. *Postural control during reaching in young infants: A dynamic systems approach.* NEUROSCI BIOBEHAV REV **22**(4)507–514, 1998.—We conceptualize the coordinated development of posture and reaching within Schöner's (Ecological Psychology, 7:291–314, 1995) dynamic model of coupled levels of control: load, timing, and goal. In particular, the goal of postural stability must be maintained during a reach. Using longitudinal data from four infants followed from 3 weeks to 1 year, we show that coordination of the head with upper and lower arm activity is critical for successful reaching. First, infants acquire stable head control several weeks before reaching onset. Furthermore, reaching onset is characterized by a reorganization of muscle patterns to include more trapezius and deltoid activity, serving to stabilize the head and shoulder and provide a stable base from which to reach. We argue that initially, the system is working on postural stability and reaching as goals. Infants secondarily select appropriate muscle patterns to achieve those goals depending, in part, on their individual body sizes, body proportions and energy levels. Motor development proceeds as a continual dialogue between the nervous system, body, and environment. © 1998 Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

> ''No functional movement, such as reaching, exists, except as embedded in a complex situation and nested into a given postural setting. Both the environmental context and the postural context affect the nature and success of movements''(23)

THE IDEA that every movement is embedded in a situation and nested into a postural set is now an accepted tenet of motor control (5,4,21,22). For the most part, researchers studying adult reaching, pointing, and grasping movements try to isolate the trajectory itself by constraining the participants' trunks, reducing the degrees of freedom of the reaching arm, and by limiting the contexts to those under strict experimental control. While these experimental constraints are necessary to simplify the research questions, it is easy to lose sight of the complete interdependence of the movement of the arm on the whole body posture in natural movements, where people reach from different positions, at different speeds, while still or moving, with the other arm free or engaged in other tasks, and so on. For example, without a stable postural base of support, the inertial effects of a vigorous arm movement would cause a person to miss the intended target as balance is lost. Likewise, accurate reaching is impossible when torso and head are unsteady.

The need for coordination between posture and reaching is especially evident during early development. Infants first reach and grasp objects several months before they can sit without support. Thus, it is common to see reaching perturbing posture, as when infants just learning to sit or stand topple over when reaching for a toy just beyond their limited range of balance (20). Similarly, we can see the effect of emerging postural skill on the control of the arm (13,25,24). For example, Rochat (24) showed a shift from bimanual to unimanual reaching with the onset of stable self-sitting.

While these examples demonstrate clear links between postural development and changes in reaching skill, the specific nature of this relationship is still poorly understood. What is needed, then, is a deeper understanding of how postural systems and reaching systems are coordinated in the real-time behavior of reaching for objects and how this relationship changes over development. We contend that the complex coordination of these two simultaneously developing systems is best captured by a multi-level dynamic systems approach. In this paper, we will outline the main conceptual ideas behind a multi-level dynamic systems approach to the study of the development of reaching skill. Then we will briefly sketch, using an example from a longitudinal study of infant reaching, the implications of this multi-level approach for the study of posture and reaching.

MULTI-LEVEL DYNAMICS

Learning to reach is a non-trivial problem due to enormous biomechanical and neural complexity. The task for the young infant is to get the hand to a visually specified target in three-dimensional space. This requires the

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transformation of visual-space to a body-centered coordinate system, followed by the generation of an appropriate smooth, straight pathway from start to target, with a rising and then falling velocity. The trajectory must be produced by muscle activity that both supports the arm against gravity and generates the forces needed to move the hand to the target. At the same time, the neuromotor system must take into account the passive and elastic forces generated by the movement itself, particularly during fast movements when these forces are large.

A recent theoretical model by Gregor Schöner (27) provides an insightful entry into the complexity of learning to reach. His model of trajectory formation during goal-directed arm movements is comprised of three levels—goal, timing and load. Each of these levels is defined as a functional system that stabilizes a class of behavioral variables against a particular class of perturbations. At the goal level, global parameters of a movement such as target direction and distance are stabilized against global perturbations such as a transient shift of target location prior to the onset of movement. At the timing level, the specific spatio-temporal characteristics of an action such as the frequency of rhythmical movement are stabilized against timing perturbations such as a transient increase in movement frequency. Finally, at the load level, the mechanical properties of a movement such as the forces generated by muscle contraction are stabilized against phasic mechanical perturbations such as the transient application of an external weight to the arm.

Within this dynamic view, the time-dependent behavior of goal, timing, and load level variables (movement direction, reaching trajectories, forces generated during a reach) are emergent from the cooperative interaction of system components (and their histories) within a particular task and environmental context (27,31,35). Critical to the study of these behavioral patterns is their topography and stability, particularly in the face of varying circumstances. For instance, adults' typically straight, smooth reach trajectories retain a recognizable topography over many different speeds and directions. This spatio-temporal topography can be considered an 'attractor', pulling together many components—joints, motoneurons, etc.—into a coherent pattern of coordination.

It is important to emphasize that the dynamics within and across goal, timing and load levels are neither hierarchical nor anatomical. Rather, they are mutually and reciprocally coupled. Under special conditions, however, we can study the dynamics of one level in isolation because some experimental manipulations perturb variables at one level while holding the other levels constant. For instance, manipulations of the time allowed for trajectory planning once a target location appears can reveal properties of goal level control while keeping trajectory and force characteristics of the movement largely unchanged (28,18). Similarly, in now-classic equilibrium point experiments, properties of load level control are revealed when goal and timing levels are held constant by instructing participants 'not to intervene' when their arms are mechanically perturbed (11). While these examples help clarify the theoretical concepts we are using, it is important to keep in mind, particularly when studying development, that these levels are generally highly interactive in natural movements.

We contend that Schöner's theoretical model is very useful for thinking about the development of trajectory control, and we suggest two hypotheses derived from the model. First, we hypothesize that in the initial state of learning, goal, timing, and load levels are tightly coupled. What develops is precisely the ability to flexibly and independently control levels as is needed for the task. Second, we hypothesize that these levels, while not functionally hierarchical, develop sequentially. That is, infants must gain some measure of control over the load level in order to maintain stable timing dynamics, and, likewise, they must gain some control over load and timing levels to be able to protect their goals from perturbation.

We illustrate the utility of this approach for understanding the developmental course of learning to reach, and later, show how the same framework can illuminate the emerging control of posture and reaching.

THE DEVELOPMENT OF REACHING: A DYNAMIC SYSTEMS STUDY

Based on dynamic systems principles, we conducted a study of learning to reach in which we tracked, within individual infants, the emergence and subsequent improvement in reaching skill. Two aspects of our research design were motivated by a multi-level dynamics systems approach. First, we measured variables across multiple measurement levels. Second, we measured each variable densely across each relevant time scale—within a trial and over development. Four normal babies participated in the study—Nathan, Gabriel, Hannah, and Justin. These infants came into the laboratory twice each week from 3 until 30 weeks and then every other week thereafter. At one of the weekly visits, infants were seated in a specially designed infant seat in an almost vertical position with their torsos supported, while we presented toys to them in midline at shoulder height. We used a four-camera WATSMART system and surface electromyography to track the movement of both arms in 3-D space (150 Hz) and associated muscle patterns (750 Hz) of the biceps, triceps, anterior deltoid and upper trapezius. The details of the data collection and analyses are available in Thelen et al. (34,9,33,29). At the second visit, we videotaped the infants in a semi-structured play situation, where parents were told to interact naturally with their infants, playing with an array of toys placed nearby. Infants were positioned in three different postures: supine, prone and seated (first in an infant seat and, later, sitting alone). These videotaped sessions were continuously coded for postural and manual activities.

THE COUPLED DYNAMICS OF LEARNING TO REACH

The emergence of reaching control can be captured as changes in the spatio-temporal characteristics of the route of the hand as it traverses from start to target. It is well-known that when infants first reach out to touch and grab objects, their movements are tortuous and indirect, tracing a sinuous path to the target consisting of several velocity bumps and valleys, known as 'movement units' (37). Over the first year, infants become better reachers as indexed by these variables. Figure 1 depicts week-to-week changes in two conventional measures of the 'goodness' of infant reaching for the four infants we studied: the straightness

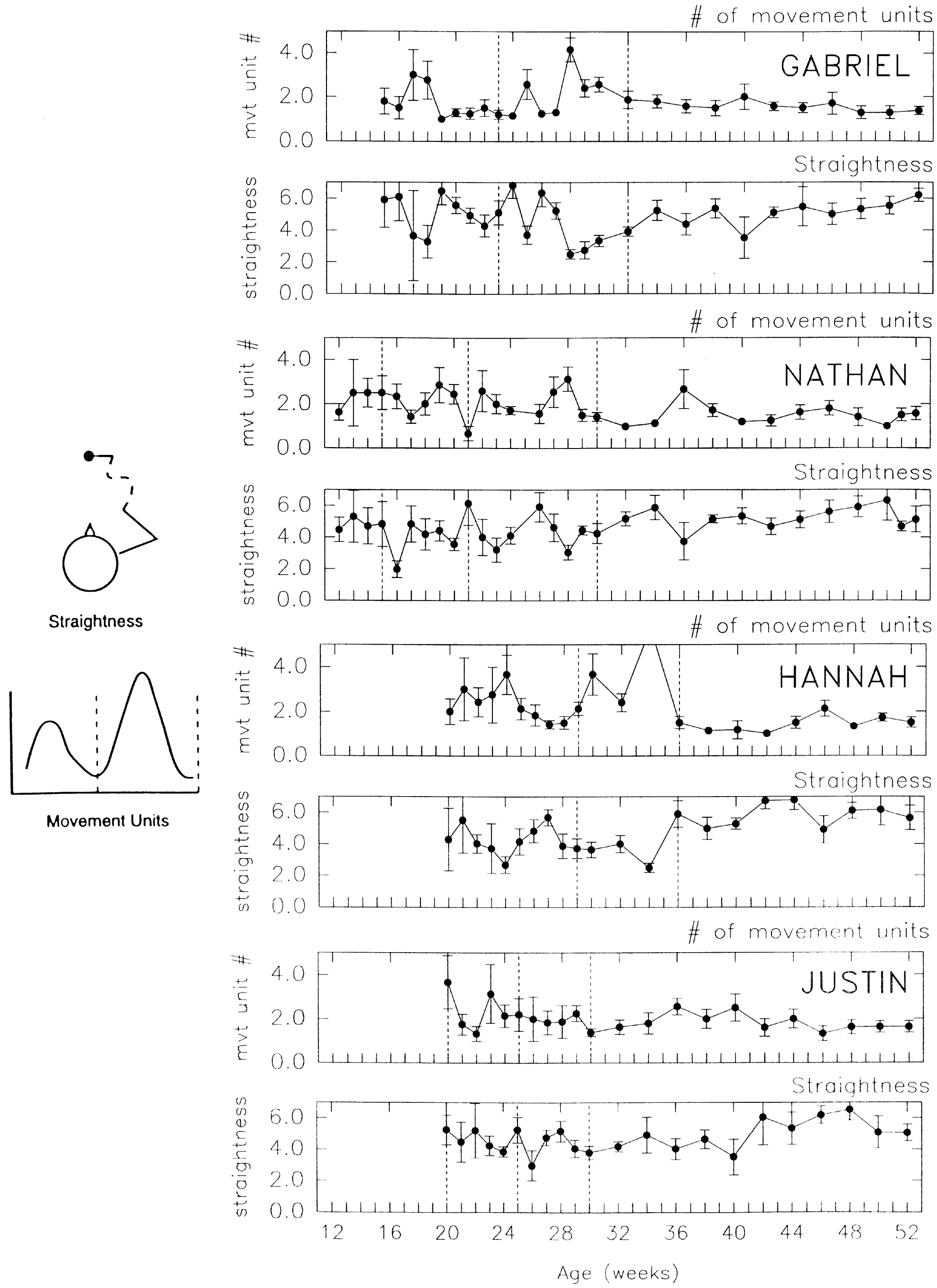

FIG. 1. Longitudinal measures of reaching improvement over the first year in four infants. Means and standard errors of the number of movement units and straightness index as a function of age. Number of movement units, a measure of hand-path smoothness, was determined by an algorithm that identified above-threshold increasing and decreasing hand speeds. A movement unit was defined as a speed maximum between two minima, where the difference between the maximum speed and both minima exceeded 1 cm s^{-1}. Straightness index was the ratio between the virtual path, a straight line from the 3-D coordinates of reach initiation to toy contact, and the actual hand path length. The obtained 0 to 1 interval ratio was then standardized using the following Z-transform equation: $z(x) = 2\ln((1 + x)/(1 - x))$. Increasing values indicate straighter paths (33). The first dotted line from the left indicates the onset of the active period, characterized by increased reaching and non-reaching movement speeds. The dotted line furthest to the right indicates the onset of the period of stable reaching.

of the pathway from start to target (the ratio of the direct path to the real path) and the smoothness of the pathway measured by the number of movement units. These variables index infants' increasing control over their arms and show improvement toward more straight and smooth reaches.

While reaching improved overall, the developmental course of these improvements was not linear. Several shifts are notable. First is the onset of successful reaching, which differed considerably among the four infants, ranging from 12 weeks for Nathan to 20 weeks for Hannah and Justin. In the first weeks after onset, reaches were poorly controlled and highly variable. After a period of improvement, two of the four infants (Gabriel and Hannah) showed a peculiar regression in control where trajectories were particularly tortuous, with indirect paths and many movement units.

This degradation in reach quality occurred despite two months of reaching experience (see Fig. 1). In contrast, around 30–36 weeks of age, all four infants began a stable period marked by a reliable reaching configuration with straight paths and 1–2 movement units.

What is going on?

These non-monotonic changes in reach trajectories are best understood by the dynamic model, where timing and load levels are tightly coupled. Consider the surprising regressions in trajectory control seen even after several months of reaching. Importantly, these regressions occurred during periods when infants' reaches were notably fast (33). (We do not know *why* infants reached faster at certain ages, but fast reaching was accompanied by faster nonreaching movements as well, suggesting it was a nonspecific change of movement vigor.) Why would speed be associated with a degraded trajectory? Adults can maintain good trajectory control at a wide range of movement speeds.

Fast movements are generated by strong muscle contractions producing large forces. In a linked mechanical system such as torso and multisegmented limbs, the forces generated at any one segment also generate passive forces on the other segments. (Passive is used in the sense that these forces are not directly controlled by the nervous system.) One critical aspect of skilled movement is the ability to stabilize the linked segments against these motion-dependent forces. An example would be holding your body stable while pushing a very heavy door, or holding your wrist stable while hammering a nail.

An explanation consistent with the dynamic model is that when infants first learn to reach, the forces generated from fast movements disrupt the ongoing movement, making the reach trajectory unstable. This suggests that the timing and load levels are tightly coupled early in reaching skill development—infants cannot protect their timing level dynamics from force perturbations generated at the load level during fast movements. Stable reaching emerges as infants learn both to slow down their movements and to use strategies that preserve good trajectories at different speeds.

Indeed, one strategy that can be used to dampen out load level perturbations at fast speeds is to make the arm stiffer or less compliant. Thus, if the high forces produced during fast movements are indeed perturbing, one might see an increase in muscle coactivity during fast movements to counteract forces moving the hand in unwanted directions. Later, less coactivity may be needed in fast reaches as skill at generating forces in more precise directions develops. This indeed is what we found in our analyses of the amount of muscle coactivity infants used in fast, medium, and slow speed reaches across the first year. Early in the first year, infants' fast reaches were highly coactive in comparison with medium and slow speed reaches. By 30–36 weeks, however, when infants' reaching trajectories became smooth and straight, the amount of coactivity across fast, medium, and slow speed reaches was comparable (29).

This developmental picture of learning to reach is consistent with the notion that in unskilled movements, the levels of control cannot be independently maintained. In a sense, infants begin by being prisoners of their biomechanics, and only later, do stable movement pathways and goals emerge; the attractor dynamics evolve gradually across levels.

IMPLICATIONS OF A MULTI-LEVEL DYNAMICS APPROACH FOR POSTURE AND REACHING

While Schöner's multi-level dynamical theory has had important conceptual implications for the study of reaching, implications for the study of posture and reaching are not transparent. A conceptual link can be made, however, when one considers recent studies of postural control. For example, Schöner (26) modeled the dynamics of postural control in a 'moving room' paradigm in which the room oscillated at low frequencies. The important point for our purposes herein is that adults' postural control in such conditions retains a spatio-temporal topography that can be considered an attractor, pulling together a wide array of components. Similar results have been obtained in studies of postural stability in children and infants (6). From these studies, we can conclude that real-time and developmental changes in postural control can be described in the same language—dynamic systems—as real-time and developmental changes in reaching skill.

Following from this conclusion, posture can be thought of as an additional level of dynamics coupled to the goal, timing, and load levels of Schöner's model. This conceptual model of posture and reaching is generally not considered in studies of adult reaching because the coupling between posture and reaching is weakened substantially by fixing the torso and upper arm, locking the movements of specific joints, etc. Under these conditions, the posture/reaching system can be adequately described by the topography and stability of attractors at the goal, timing and/or load levels. More generally, however, posture and reaching levels will be mutually and reciprocally interactive. This is clearly seen in studies of both adult and infant reaching in which more global body movements are allowed (7,20).

While detailed dynamical descriptions of the posture and reaching systems have yet to be realized, this multi-level dynamic view offers a unified theoretical framework within which one can examine how posture and reaching are coordinated over real-time and development. As a first step in exploring the empirical implications of the multi-leveled view, we examined how postural control of the head might relate to the onset of successful reaching in infancy.

POSTURE AND THE ONSET OF REACHING

To reach and grasp objects, infants must maintain stable vision of the target as they lift their arms without perturbing the head and torso as a consequence of arm movement. Both require strength and control of neck and shoulder muscles to provide such postural stability. Our data indicate that emerging postural control of the head may play an important role in the onset of successful reaching, but this emerging control must be coordinated with the demands of reaching out to a target location.

For the first months of life, supine infants characteristically assume the asymmetric tonic neck posture and cannot move their heads to midline. This indicates poor head control. To determine the age at which the infants in our longitudinal study gained good head control, we coded

TABLE 1
ONSET WEEK OF HEAD CONTROL IN SUPINE AND FIRST SUCCESSFUL REACHING

Infant	Onset of head control	Onset of successful reaching
Nathan	9	12
Gabriel	12	15
Hannah	12	20
Justin	15	20

infants' preferred head position while they were supine during the naturalistic play sessions. We used the age at which infants assumed a midline head position for 50% or more of the observation session as an index of head control. These ages are listed in Table 1 for each infant along with the age of reaching onset. Overall, each infant showed good head control several weeks prior to the onset of reaching. Thus, head control may be a necessary precursor to reliable reaching; however, it is clearly not sufficient since, on average, 4.7 weeks elapsed between the time of head control onset and reaching onset.

While it is possible that head control and reaching onset are only loosely related, data from our reaching sessions suggest that head stability played an important role in the emergence of successful reaching. One of the unique aspects of our longitudinal study was recording arm kinematics and muscle patterns in the weeks *before* infants actually reached for toys. When we compared these pre-reaching movements to goal-directed reaching, we found a dramatic reorganization of muscle patterns at reaching onset. In Fig. 2, we show muscle patterns in pre-reaching and reaching movements as a function of the frequency of all possible patterns of co-activity of the four monitored muscles: biceps, triceps, anterior deltoid and trapezius (29). First, note that although this yields 16 possible combinations, some combinations of muscles are rarely, if ever, seen. But among the preferred muscle combinations, reaching involved much more use of trapezius and deltoid muscles both alone and in combination. By contrast, pre-reaching muscle activity was more likely to be dominated by biceps and triceps. Further analyses revealed that these changes from biceps/triceps to trapezius/deltoid combinations occurred dramatically within 1–2 weeks of reaching onset (29). In addition, these differences were not a function of infants moving to different areas of the work space when

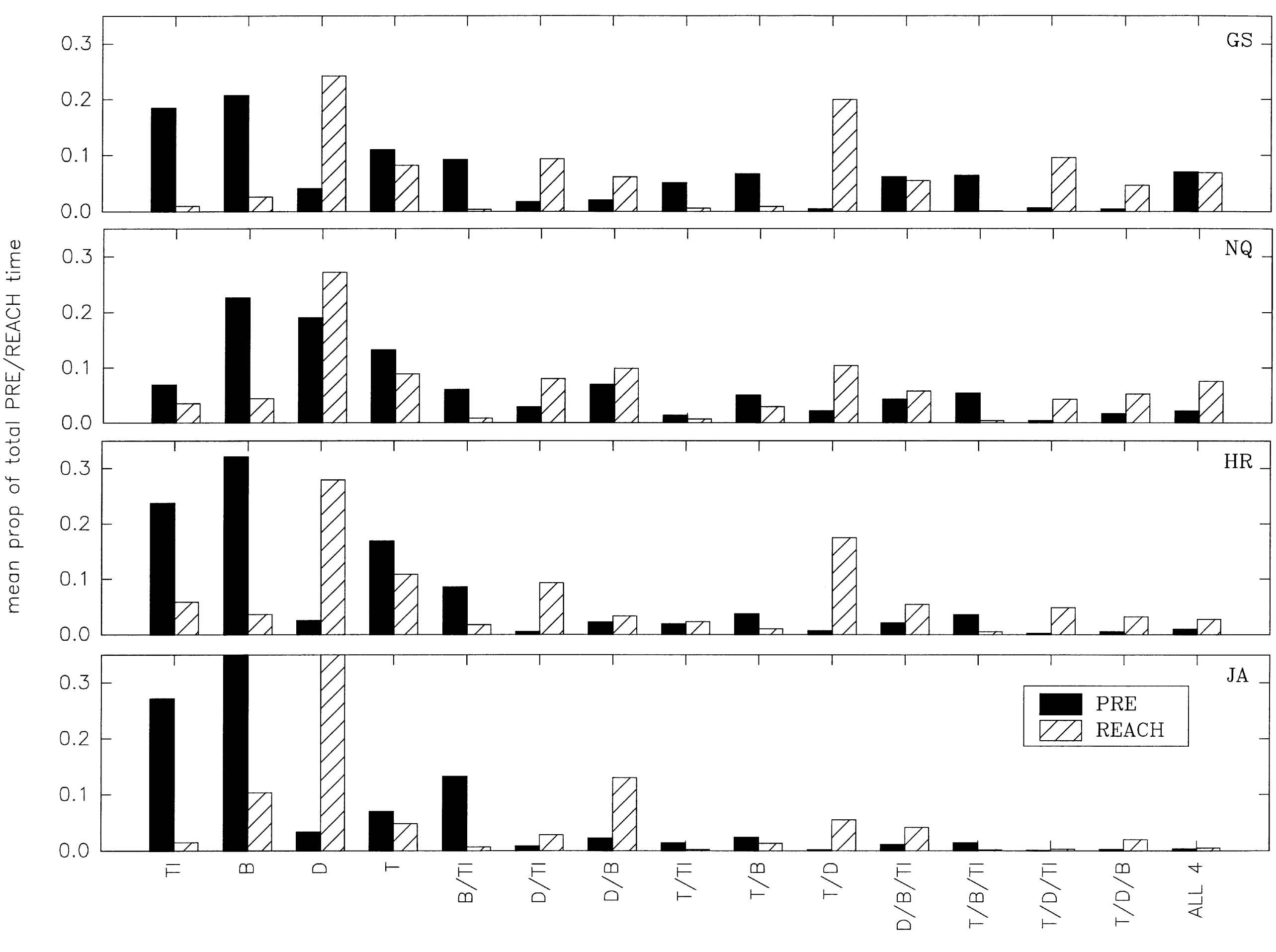

FIG. 2. Mean proportion of time each muscle combination occurred for the pre-reaching and reaching periods for each infant. Data for one infant (Gabriel, GS; Nathan, NQ; Hannah, HR; Justin, JR) are presented on each graph. Muscle combinations are labeled using the following abbreviations: trapezius, T; deltoid, D; biceps, B; triceps, TI.

reaching. When we normalized the muscle state frequencies to the actual time spent in 11 areas of the 3-D space, the shift in dominant muscle patterns persisted (29).

The new pattern of muscle activity infants discovered at the onset of reaching indicates that coordination of the head with upper and lower arm activity are critical for successful reaching to midline. The increase in trapezius and deltoid activity could serve to stabilize the head and shoulder, thereby providing a stable base from which to reach. In addition, deltoid activity and the associated absence of biceps and triceps provided the force needed to direct the hand up and toward midline. These results are consistent with data from Flanders (12) showing that anterior deltoid is a primary agonist for reaches from the side to midline. Thus, infants learned more than how to control their heads in the weeks following the onset of head control— they learned how to hold the head steady while the arm is moved away from the body, i.e., how to stabilize postural dynamics in the face of potential perturbation from uncontrolled arm movements.

CONCLUSIONS

In the framework of the dynamic model, early reaching is constrained by head and shoulder instability because the coupled systems of posture and reaching are not independently controlled. Infants cannot hold the arm steady against the perturbations of the wobbly head (nor can they maintain a steady visual target). Likewise, infants must acquire the ability to differentially lift the arm without disrupting head and torso. Our muscle activity data indicate that this requires stronger activation of shoulder and neck muscles in relation to earlier reliance on the elbow flexors and extensors.

Our data and the studies of others (13,24,25) thus point clearly to an intimate relationship between posture and reaching, emphasizing the critical role of head and torso stability for the emergence of good trajectory control. What is needed now is more research on the precise mechanisms by which stabilizing control is attained and their developmental pathways. One promising line of research suggested by the dynamic model is to test emerging control through selective perturbations of the component levels. Studies conducted by Von Hofsten (38), Kamm (20), Rochat (24), and Savelsbergh and van der Kamp (25) make strides toward this aim.

THE ALTERNATIVES TO A DYNAMIC SYSTEMS APPROACH

We have proposed here that a dynamic systems approach offers a comprehensive framework for understanding the development of posture and reaching. What are the alternatives?

One alternative to consider is the more traditional neurophysiological perspective. For example, Hirschfield and Forssberg (19) recently proposed a *central pattern generator* (CPG) model of posture, and this idea has been extended to postural development in several recent papers (16,17). According to this view, infants are born with a number of innate and predetermined neural connections (CPGs) which change and mature through endogenous (experience-independent) processes. Experience selects or refines these pre-existing muscle patterns, but the emphasis is on the CPG with maturation as the primary agent of change.

There is no disagreement with the fact that infants are born with a species-typical neural anatomy, and that this anatomy forms the basis for further epigenetic changes. How could it be otherwise? There is also no disagreement that even at birth, some movements and muscle patterns are possible and others are not. Several other aspects of the CPG account are problematic, however.

First, several lines of evidence suggest that muscle patterns seen in infant movements do not fit any of the accepted definitions of the central pattern generator. Recall that in the original formulations, the CPG was a network of neurons located in the spinal cord that could generate the muscle-specific and rhythmical activations of natural locomotion in the absence of sensory input (10,15). The role of sensory input was to modulate this intrinsic pattern. Thus, the defining features of a CPG were (1) specific patterns of muscle activity, (2) muscle patterns that were used for functional behavior and (3) muscle patterns that could be generated autonomously, even though they normally may not be.

We now have considerable data on limb and trunk muscle patterns in human infants during kicking and stepping (14,34), sitting (16,17) standing (39), reaching (32,29), and walking (1). In no case do these data show evidence of these defining features. Researchers have failed to identify precise patterns of flexion and extension that map directly onto the kinematics of the movement, as might be generated by a CPG. On the contrary, all investigators report very high variability, with infants using many possible combinations of muscles, including considerable co-contraction.

Equally compelling is the lack of evidence that any part of the nervous system develops or matures autonomously (just as a function of time) and independent of peripheral input. There is, in contrast, considerable evidence that peripheral input can modulate movement patterns at birth (3) and even prenatally (8). Moreover, at just a few months of age, infants can learn quite specific and complex limb coordinations within a few minutes of training (30). Effects of longer training have also been noted for stepping movements (36,40) and posture (17).

Without these defining features, there is no basis to call infant muscle patterns CPGs, or to envision them as distinct or different from any and all other neural networks. Indeed, according to Hadders-Algra, et al. (16,17), the CPG has been redefined to be ''neural networks co-ordinating the activity of many muscles'' controlled by reticulospinal neurons that can be modulated by afferent input. In this usage, 'CPG' is no more informative than 'nervous system.'

More fundamentally difficult are the assumptions made by proponents of a strictly neurophysiological view of a one-to-one mapping between patterns of muscle activation and motor behavior. The purpose of muscles is to create forces or torques that rotate body segments. Since Bernstein (5), motor scientists have understood that the translation from muscle activation patterns to force generation is highly complex and multiply-determined, with many combinations of muscle firings potentially producing the same motor outcome. Even for the same activity, different individuals may prefer quite different muscle patterns.

What is at stake developmentally is that the nervous system may not particularly care about the precise patterning of muscle activations, but is rather controlling some other variable, perhaps final posture or relative force production, depending on the task. It is clear from our data on reaching, for example, that initially, infants need to solve a load level problem, that is, to modulate forces to get their hands in the vicinity of the target. While infants solved this problem using a globally similar collection of muscles in different regions of the workspace (29), there were substantial individual differences in the specific patterns of muscle activity infants used from reach to reach. This was in part due to individual differences in the general speed with which infants moved (32). Thus, no specific patterns appear to be built in because the nervous system cannot anticipate ahead of time the relative vigor of an infant's movements.

The same is true of newly walking infants. In a longitudinal study of the transition to walking, Angulo Kinzler et al. (1) found that patterns of flexor and extensor torque production at the hip and knee during the swing phase was quite invariant among and between newly walking infants, but that there was enormous variability in the underlying EMG patterns. What is the central nervous system working on? One likely possibility is that the nervous system is trying to stabilize the hips in space as the center of gravity is shifted laterally and forward (2) with alternating swings of the legs. These goals of propulsion and postural stability are more important than the precise muscle patterns used to accomplish them. Indeed, as in reaching, infants may have different stability requirements depending on their body size and build as well as their motor strength and control.

The elegant data of Hadders-Algra et al. (16) tell an identical story. These authors showed that infants just learning to sit used nearly every possible combination of flexors and extensors in response to platform translation. The infants wanted to remain seated and not topple over. Thus, they recruited whatever muscles they could to keep their centers of gravity over their bases of support. Again, it would be maladaptive to have a restricted set of synergies or CPGs built in because body sizes, strength, energy level, and so on are individually determined, and initial positions vary with each trial.

In each of these cases, infants may ultimately converge on similar muscle activation patterns, but that convergence is a *consequence* of development within the constraints of the intrinsic neuroanatomy, physical and social environment and the specific task at hand, not because of some autonomous and as yet unknown maturational processes. In Schöner's (27) terms, muscle patterns may not be a controlled variable, i.e. a variable that the nervous system stabilizes against perturbation. The goal of developmental research, then, is (1) to identify which variables *are* controlled by the nervous system and (2) to investigate how the dynamics of these variables change over development. While we have not yet realized these research goals, our longitudinal reaching data illustrate how variables at multiple measurement levels can contribute to global progressions and regressions in development, thereby pointing toward a dynamic systems approach and away from a strict neurophysiological view.

Because development is always a continual dialogue between the nervous system, the body, and the environment, we need a theoretical language that captures this interaction. Although the nervous system is a critical element in this triumverate, it is not singularly causal. Rather causality lies only in the interactions. Nervous systems respond to bodies and environments just as much as bodies respond to nervous systems. Dynamic principles are helping us to begin to understand these nested and coupled relationships.

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