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Brain, Body, and Mind: Lessons from Infant Motor Development

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## Brain, body, and mind: Lessons from Infant Motor Development

*“One cannot simply ‘peel away’ the body to understand the nervous system’s role in adaptive behavior”*

*(Chiel & Beer, 1997, p. 554)*

The body is the host of our thoughts. It is with our body that we think, express emotions, reach states of mind, and formulate intentions. Although these mental processes are usually seen as the direct product of brain activity, they are inseparable from the body in which they reside, and with which they are actualized. These embodied expressions of brain activity occur continuously, moment by moment, whether we are letting our thoughts wander while strolling along a pathway or whether we are thinking hard while sitting still in front of a computer. The body is also the crucial pathway through which our language, gestures, and actions are actualized and perceived by others. It is in concert with the body, and through the mastery of its intrinsic physical and physiological properties that we learn to express, direct, perceive, receive, feel, and continuously exchange information with the environment. In sum, the body with its physical properties is the vital liaison between the mind and the outer world and this liaison is constant throughout the lifespan as we grow and interact with the environment.

Can we ignore the body when studying the development of the brain and the mind? Is it possible to conceive a mind, pure and autonomous, that would not take into account, would not be influenced by, or would function independently from the body in which it resides? Could our thinking and reasoning, even in their most abstract form, grow and evolve without such a fundamental, bodily connection to the outer world? Despite the fact that body and mind are continuously and tightly interconnected in time, cognitive sciences have largely neglected the

former to focus mainly on the later. Body and mind have been defined mostly hierarchically. The mind guides, commands, decides, discovers, and organizes, while the body executes, expresses, or simply reflects the commands or states dictated by the mind. This neglect of the body has become even more extreme today as theoretical and technological advances have made it possible to study the brain -- the site of the mind -- more closely. Computer models simulating complex neural networks have emerged as a powerful way to understand the mind and its formation, however in many instances, such models study a mind denuded from its body.

The goal of this chapter is to focus on the role that the body plays in the process of brain and mind formation. To do so, I borrow heavily from work on motor development that was performed from a dynamic systems approach. Dynamic systems and connectionist perspectives share common interests in their attempts to understand brain, behavior, and mind, however, dynamic systems approaches have been more prone than connectionists approaches at considering the body -- its physiological and biomechanical properties -- as a crucial component to the formation of behavior and thought. I begin this chapter by reviewing briefly some theoretical concepts about embodiment and the dynamic systems approach (for more extended tutorials on the dynamic systems approach see other chapters in this book or sources such as Kelso (1995) and Thelen & Smith (1994)). Then, I concentrate on three examples on infant motor development that illustrate the strong coupling existing between the body and the mind in development and highlight the usefulness of accounting for the body and its properties when investigating a developmental question. In the conclusions, I extend the theme of this chapter to situations that do not involve motor activities per se, to illustrate that even such activities can be embodied. Overall, the theme of this chapter is to show that development is a process marked by continuous perceptual and sensory-motor experiences which involve a brain with a body that can

act and sense. I will argue that those perceptual and sensory-motor experiences are crucial for brain, mind, and behavioral development and that they create the foundation of many forms of thinking in development.

### 1. Dynamics Systems and the Embodied Brain: A Brief Overview

In 1997, Chiel and Beer published a wonderful paper in *Trends in Neurosciences* in which they offer a contrasting view to the commonly held one that the body is a mere acting device, subordinated to the commands of the mind. In that paper, they make a very simple, seemingly obvious, however extremely fundamental point, namely, that the brain is completely embedded in the body, and that the body, in turn, is completely embedded in the environment. Because of this embeddedness, the body is an obligatory pathway between the mind and the environment and therefore understanding the brain should be done by including the body in which it resides. Chiel and Beer (1997) also argue that the body, just like the brain and the environment, is a complex and highly structured dynamical system that has unique intrinsic mechanical and musculoskeletal properties. These properties are inherent to patterns of sensory and muscle activation and constitute a fundamental influence on the process of neural activity and change over time. Finally, Chiel and Beer (1997) argue that brain, body and environment are continuously coupled to one another through time, and that adaptive behavior emerges from the interaction of all three coupled components.

Chiel and Beer's view of an embodied brain is fully compatible with the dynamic systems approach. From a dynamic systems perspective, brain, body, and mind are not dissociable from one another. In fact, as discussed by Thelen (2000), there are no points in time

where the mind is not embedded in the body, and there are no points in time where the brain does not receive information from the body. What changes with development and time is the nature of the coupling between brain, body, and environment. Thus, mind formation and the creation of more abstract forms of thinking over time can be seen as the product of this continuous change in coupling.

From a dynamic systems perspective, the body and its musculoskeletal properties can be important contributors to the process of change. The body with its particular perceptual and motor capabilities can fully participate in the processes that form mind, brain, and behavior. Furthermore, because change is the product of continuous, intricate, and multileveled interactions among brain, body, and the environment, one cannot establish a hierarchical order between these elements, nor is there one element that is more privileged than the others in driving change (see Schöner, 1995; Steinhage & Schöner, 1997, for example). The brain does not hold a particular or privileged status; rather, the brain contributes in concert with the body and the environment to the dynamic process of behavioral and mind formation. Just as a symphony emanates from the cooperative activity of the many musicians and their instruments in the orchestra, behavior and thought emerge from the active interactions of the many parts and components of the organism in its environment.

For researchers interested in development, studying change and capturing the processes of change is of primary importance. The fact is that change occurs continuously, no matter the time scale or magnitude of change. Behaviors, thoughts, or states of mind do not have an enduring, definite quality; they evolve continuously, form, dissipate, and eventually reform as a function of time and interactions between elements of a system. Those changes are also closely linked to the kind of experiences that are associated to having a body with a particular set of

perceptual and motor capabilities (Thelen, 2000). Those experiences, their behavioral and cognitive outcome, and the developmental changes they entail are not fully independent from the way the body -- its perceptual and motor systems -- is being organized over time.

In sum, brain, body, and environment all play a central and intertwined role in the process of developmental change. Whether one loses a limb, gains weight, discovers how to use computers, carries a heavy load, falls in love, or acquires the meaning of a new word, all these examples have the potential to alter dramatically the way individuals, their body, brain, and mind, perceive, act, and interact with their environment.

In the following sections, I use examples from research on motor development to illustrate specifically how the body, its characteristics, and specific sensory-motor experiences emanating from using the body in particular ways can play an integral part in the process of behavior and mind formation, and can impact neural organization. The behaviors I present and discuss here after relate to different aspects of the development of reaching during the first year of life of infants. They relate to the emergence of voluntary reaching around 3-4 months of age, reaching in the context of the A-non-B task around 8-to-10 months old, and the fluctuation of patterns of reaching throughout the first year of life. These three aspects of the development of reaching have been heavily studied, but the explanations provided to account for the observed developmental changes in reaching are consistent and more in line with traditional, non-embodied views of cognition. Those views assume, for example, that infants reaching patterns are guided by vision and the mind, that they directly reflect the infant's state of reasoning or understanding of a particular situation at a particular point in time, or that they are the product of inborn or autonomous maturational changes in the brain. In the sections below, I will revisit those interpretations and show that when we acknowledge the role that the body and its sensory

and motor characteristics play in the observed behavioral phenomena, another level of understanding emerges. In all three cases, I begin by presenting the behavioral facts and their classic interpretations, and then I present the corresponding alternate interpretation from a dynamic systems, embodied perspective.

## 2. Learning to Reach

The question of how young infants learn to reach for objects located in their nearby environment dates back to the first observations of Piaget (1952). How do infants, who have never reached for an object voluntarily before, come to figure out how to move their arm to where the desired toy is located? What are the characteristics of their movement on their first reaching attempts? And how do infants progress over time? Piaget (1952) contended that early reaching emerged from seeing the hand and the toy simultaneously in the same visual field. From that moment, reaching developed from a process of gradual guidance of the hand toward the toy, in which the infant glanced successively and alternately between hand and toy to bring the hand step-by-step closer to the toy. Piaget's observations set the stage for the long lasting interpretation that reaching develops primarily under the guidance of vision. Subsequent studies that examined the development of reaching in finer detail by analyzing the movement kinematics of young reachers, found that during the few months following the onset of reaching, infants produce highly meandering, indirect, zigzagging, discontinuous hand paths to the toy (Fetters & Todd, 1987; Mathew & Cook, 1990; von Hofsten, 1979, 1991). These indirect trajectories were assumed to reflect the stepwise process of visual guidance of the hand, where the infant reassessed the position of the hand relative to the toy's position after each move and made

successive corrections to bring the hand progressively closer to the toy. This early period of discontinuous hand trajectories was later labeled “visually guided” (see Bushnell, 1985; Streri, 1991, for reviews) and was very much in line with a cognitive approach to development where the mind commands the body.

This interpretation that early reaching is visually guided came into question in the late 80s and early 90s by a number of studies performed by Clifton and collaborators (Clifton, Muir, Ashmead, & Clarkson, 1993; Clifton, Rochat, Robin, & Berthier, 1994; Perris & Clifton, 1988). These researchers demonstrated that young infants do not really need to see their hand to bring it to the toy; young infants can attain a target in the dark without seeing their hand or solely on the basis of auditory information, that is, without seeing the target either. This work raised a critical new question. If young infants do not need to visually guide their hand to reach for a toy, why is their movement trajectory to the toy so convoluted? Why do infants show so many corrections in hand trajectory before attaining the target?

The answer was brought by another group of researchers, who discovered that the deviations in arm trajectory that are typical of infants’ first attempts to reach arise from the interactions of the infants’ own level of activity and intrinsic biomechanical properties of the body and arm at work (Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; Thelen, Corbetta, & Spencer, 1996). Thelen *et al.* observed that infants who were more active and, thus, moved their arm toward the target faster, also tended to generate more discontinuous movements, while infants who were calmer and moved their arm much more slowly, appeared to display much straighter trajectories to the toy. To understand this link between activity level and movement discontinuity, Thelen *et al.* analyzed the movement speed and trajectory patterns of the reaches in relation to the inertial forces that were generated by the infants’ movements as

they directed their hand toward the toy. They found that fast movements were associated with high motion dependent torques which tended to drag the arm away from the intended goal location. Thus, the active infants who produced these high speed motion patterns had to take into account these motion intrinsic generated forces to attain the toy; they had to use their muscles not only for initiating movement, but also for breaking these deviations in trajectory and repeatedly redirecting their arm toward the toy, assumingly by matching online the proprioceptive feeling of the arm in motion with the sight of the toy. This ultimately caused the formation of convoluted hand paths to the toy. In contrast, the slower movements of the quieter infants appeared much more direct simply because they did not generate disruptive torques during the movement.

Thus, from this work it appeared that the discontinuous trajectories of the arm to the toy were not the result of stepwise visual guidance of the hand, but rather the product of the amount of energy that infants were bringing to the task of reaching for the objects. High energy levels generated high speed movements and high motion dependent torques which interacted with the infants' plan or intent to direct their hand to the toy. Alternatively, low energy levels required mainly generating muscle strength to lift the arm and maintain it against gravity. Hence, learning to reach, attaining the toy, and improving movement directness over time, required that infants discover unique movement solutions that were relative to their individual levels of energy; active infants needed to slow down their movement and quiet infants needed to speed up their movement in order to attain the toy more readily. This process of scaling the movement speed to the goal involved discovering the biomechanical properties of the arm in motion. This could only be done through repeated sensory-motor experience as infants produced and practiced a wide range of movement solutions -- some fast, some slow -- and matched their respective outcome to the goal.

In this scenario, the brain and specific neural networks involved in the formation of reaching trajectories are not solely responsible for monitoring the trajectory of the hand; they are also involved in encoding and mastering the specific motion-dependent dynamics of the arm as it moves towards the goal. Those biomechanical, motion-dependent properties of the body and the arm are integral pieces and parts of the larger plan and process of learning to reach for an object and the brain cannot ignore them when directing an arm to a specific goal location. When the mind plans an action to a goal, the characteristics of the “tool” involved in the action -- the body -- must be integrated with the resultant plan. In this context, body and mind are inseparable. Consistent with this scenario, Thelen *et al.* who followed the development of individual infants over time were able to show that within a few weeks after the onset of reaching, infants learned to adjust their movements to achieve more direct reaches: the active infants learned to slow down their movements, while the slow infants were able to increase movement speed. In sum, infants learned to reach and map their actions to their intentions through the discovery of their body’s properties and more specifically through the discovery of the appropriate pattern of movement dynamics that allowed them to attain the target more directly. This developmental change in action patterns involved the coupled activity of the mind, brain, body, and environment.

### 3. Reaching in the Context of the A-not-B Task

The ability of infants to represent and retrieve objects hidden in particular locations in space is at the core of the second example used here. Piaget’s (1954) interest in the origins of intelligence lead him to devise one of the most heavily used tasks in early cognitive and motor development -- the A-not-B task. In this task, infants are presented with a surface containing two

wells located a few inches apart and both are covered with an identical cloth or lid. The infant first watches an experimenter hide a toy in one of those wells (location A). After a short delay, the infant is invited to retrieve the toy. This hiding/retrieving event to the A location is repeated a few times; then, the experimenter hides the toy in the second well (location B) as the infant watches. Eight to 10 months old infants typically make an error on the B trial; they search for the toy in the A location despite having witnessed the experimenter hide the toy at location B. According to Piaget (1954), infants fail to search at location B because they have a weak or incomplete representation of where the object is located.

Since Piaget, this error in the A-not-B task has been replicated across very large number of studies involving many variations of the task. In those studies, interpretations of the error were almost always of a cognitive nature, neglecting the role that action may play in this task (see Morton & Munakata, this volume, for an example of disembodied approach). Interpretations of the A-not-B stressed the limited memory capacity of infants, their lack of object permanence, or their inability to coordinate information in time and space (see Diamond, 1990; Smith, Thelen, Titzer, & McLin, 1999; Thelen, Schöner, Scheier, & Smith, 2001; Wellman, Cross, & Bartsch, 1986, for reviews).

Curiously enough, the A-not-B error in infancy is not limited to the context of a disappearing object. Some studies found that infants continue to make the error even when the object placed in location B remains fully visible (Butterworth, 1977), or when the task does not involve any hiding of the toy at all, but simply the repetition of reaches for a visible toy in a identical previous location (Munakata, 1997; Smith et al., 1999). Thus, from these studies it appears that the interpretations based solely on location memory or object representation are not

sufficient to explain why infants continue to make the error even when the object is perfectly visible at location B. Why then do infants make the A-not-B error?

An alternative explanation involving the body and infants' inability to control their arm flexibly during reaching was provided by a group of researchers who looked closer at the spatio-temporal characteristics of the movement (Diedrich, Thelen, Smith, & Corbetta, 2000). These researchers recorded the kinematics of the arm movement while infants were reaching to the A location for 6 consecutive trials and then when cued to the B location for 2 additional trials. They observed that at each new reaching trial to the A location, the speed profiles of the arm movements to the target became more and more alike, as if infants were progressively forming a motor template or motor "habit" of a specific reaching pattern as they were aiming repeatedly to the same location. Infants who displayed such growing pattern similarity in movement speed as a function of the repeated A trials were also more likely to continue to reach to A on the B trials, thus, making the A-not-B error. Those infants, who made the error to reach to A on the B trials, appeared to lack movement flexibility to break the motor pattern (or "motor habit") that had formed as a result of the previous reaches to A (see also Clearfield & Thelen, 2001).

Other studies from the same group of researchers demonstrated that such "motor habits" and the associated likelihood of making the error did not form when infants performed a lesser number of reaches to A before the object was switched to B (Smith et al., 1999). Furthermore, when the infant's arm was loaded with a weight, increasing movement inertia and making it more difficult for the infants to change movement trajectory, infants made the error even more frequently (Smith, Clearfield, Diedrich, & Thelen, 2006). Formal modeling of the A-not-B task and the perceptual-motor response associated with it have confirmed that the number of prior reaches to A can contribute to form a memory of the motor pattern, where brain and arm are a

coupled system. This memory of the motor pattern can be strengthened or weakened depending on the number of previous reaches to A, the motor experience of the child, the perceptual layout of the task, and other contextual factors, hence, increasing or decreasing the likelihood of making the A-not-B error depending on how these factors interact with one another (Thelen et al., 2001; Spencer, in this volume). Thus, here again, the response and errors of infants are not solely the product of infants' decisions or lack of mental representations. The mechanical and musculoskeletal properties of the body, the lack of movement flexibility required to "break" a forming reaching habit, and the number of previous trials to A, all contributed to the observed erroneous response on the B trials. Mind, body, and environment are tightly coupled in time in the formation of the response.

#### 4. Developmental Fluctuations in Hand Preference in Infant Reaching

The last example examines the development of hand preference in infant reaching. Hand preference is linked to specific brain asymmetries (Corballis, 1991; Hellige, 1993); thus, this example is useful to explore forms of coupling between brain asymmetries, body, and behavior and their evolution in early development. One strong characteristic of hand preference is that 75 to 90% of the human population displays a preferred right hand use when achieving tasks requiring a certain level of dexterity, such as writing or drawing. Furthermore, this preferred hand use is quite manifest and steady in adults. One question that has puzzled scientists for many decades relates to how such a manual preference forms. This has prompted a significant number of developmental studies and interpretations (see Corbetta & Thelen, 2002; Provins, 1997, for reviews). These interpretations have largely boiled down to two main views: one claiming that

hand preference is an inborn behavioral trait, and the other, contending that hand preference develops during childhood.

Because right-handedness is such a strong and widespread characteristic among many humans, the view that hand preference is inborn has strongly predominated (see for example Annett, 1985; McManus, 1985). A number of developmental studies have supported this view. One of the strongest pieces of evidence has come from studies that examined newborns' spontaneous head turn (Coryell, 1985; Michel, 1981; Viviani, Turkewitz, & Karp, 1978). These studies found that most newborns prefer to rotate their head to the right, and that this right preferred head turn correlates with a preferred right hand use later in early childhood. However, this connection between preferred spontaneous head turn at birth and later hand preference is not so obvious. Following the assumption that newborns' spontaneous head turn reflects an inborn behavioral bias that sets the direction of hand preference very early on, one would expect to see some continuity in hand use as infants begin to reach and manipulate objects consistent with the early bias. Yet, studies that followed the development of hand preference during infancy did not find such consistent bias in hand use; rather, they found that infants' hand preference fluctuated many times during the first year, where periods of right hand use alternated with periods of left, two-handed, or no preferred hand use (Corbetta & Thelen, 1999; Gesell & Ames, 1947; Ramsay, 1985). Some authors proposed that these fluctuations were part of the general process of brain lateralization and neuromotor maturation (Gesell, 1956; Ramsay, 1984). Nevertheless, if one assumes that hand preference is determined from birth or genetically driven as it has been suggested (Annett, 1985; McManus, 1985), the question remains as to why hand use fluctuates so much during early development. This also raises the question of how stable hand preference emerges from such a background of fluctuating movements.

I became interested in these developmental questions while collaborating with Esther Thelen and her collaborators on a longitudinal study on infant reaching in which 4 infants were followed at close time intervals over their first year of life (see Thelen, et al., 1993, 1996). In that study, we observed many aspects of the motor development of those infants, including which hand they used for reaching and when they developed new posture-related skills. All infants displayed alternating periods of one- versus two-handed reaching (Corbetta & Thelen, 1996) accompanied by periods of right versus left or no preferred hand use in reaching (Corbetta & Thelen, 1999). We noticed that developmental transitions in hand use for reaching occurred at particular times when the infants were beginning to develop new locomotor skills. The developmental pattern observed was as follow. During the early period following the emergence of reaching, infants displayed a preferred right hand bias. This right bias dissipated toward the middle of the year when infants began to self-locomote on hands-and-knees. From that time, infants alternated hand frequently, trial after trial, and week after week. Finally, toward the end of the first year, one infant began to perform his first upright independent steps. The emergence of independent walking in that infant coincided with a strong return of two-handed patterning in reaching. This was particularly surprising because at the end of the first year all infants had developed fine reaching skills, the objects were always small and easily graspable with one hand, and they were always presented at midline. Plus, all infants were highly familiar with the task, they knew exactly what to expect -- they each had months of practice reaching for those small objects with one hand. Thus, why did one infant return to two-handed reaching at the end of the first year? This was quite puzzling, particularly knowing that nothing had changed in the task, other than the fact that that infant began to walk upright.

These early observations pointed to a developmental coincidence between the emergence of self-produced locomotion and change in patterns of hand use. The question arose as to whether new levels of postural control, acquired as infants learn to self-locomote, entailed successive reorganizations of the upper limb system and changed the way infants preferred to reach for and manipulate objects. That question was examined with a couple of follow-up studies with a larger subject pool and varied tasks.

The first study investigated whether underlying preferred lateral biases in hand use would dissipate when infants begin to crawl on hands-and-knees (Corbetta & Thelen, 2002). Two groups of infants were followed over several weeks as they learned to retrieve an attractive toy concealed in a box with a lid. One group of infants was tested weekly from the time infants were 6 ½ months old and the other group was followed weekly from the age of 8 months. In the younger group, infants were not crawling. In the older group, infants just began or were beginning to crawl on hands-and-knees right around the onset of the study. All infants were tested with the same task; they had to learn how to coordinate their hands to lift and open the lid of the box with one hand while retrieving the toy from the box with other hand (see Corbetta & Thelen, 2002, for more details).

The findings from this study were quite clear. The young infants, who were not crawling, displayed a stunningly stable division of labor as they learned to solve the task over the successive weeks. In particular, many infants systematically and consistently used the same hand to open and hold the lid and used the other hand to retrieve the toy. This consistent division of hand roles to retrieve the toy from the box was very steady trial after trial and week after week to the point that most infants displayed either no or little variability in response over the whole period of testing. In contrast, the older infants who were crawling displayed extremely

changeable patterns of right and left hand use to retrieve the toy from the box. They did so within sessions and across sessions to the point that it was impossible to discern one preferred pattern of hand use (Corbetta & Thelen, 2002). These findings were consistent with our prior longitudinal observations on reaching, namely, that preferred biases in hand use present before the onset of hands-and-knees crawling disappeared when infants learned to locomote on their four limbs.

The second study looked at the development of walking and investigated whether a return to two-handed reaching was associated with learning to walk (Corbetta & Bojczyk, 2002). In this study, only one group of infants was followed longitudinally. Infants were seen weekly over the transition to upright locomotion, from the time they were 8 months old (and unable to walk), to about 2 months post upright locomotion. Every week, infants were presented with small and large objects at midline to test their one- or two-handed reaching tendencies, and they solved an object retrieval task identical to the one described above for the crawling infants. Additionally, the infant's postural and locomotor progress was tested every week to identify the week in which they took their first independent steps without support. After infants began to walk, improvement in walking was monitored by indexing the height at which they kept their arms during walking: when infants are learning to walk, they keep their arms in high guard to control balance, but as they practice walking and gain better upright balance they lower their arms along the body sides.

The results from this study were again very clear. During the *pre-walking* period, infants reached for the large objects mainly with two hands and used mainly one hand for the small ones. They also learned to open the lid of the box with one hand and coordinate the activity of their two arms to retrieve the toy out of the box without difficulty well before they began to walk. *When the infants began to perform their first independent steps, all these patterns changed.* Infants began to reach more with two hands for the small objects, they further

increased their rate of two-handed reaching for the large objects, and began to open the lid of the box with two hands as well. All these increases in two-handed performance were statistically significant (Corbetta & Bojczyk, 2002). Again, this study supported our prior observations that infants return to two-handed reaching when they are learning to walk.

These studies confirmed that the development of early hand preference is not necessarily a behavioral trait set at birth, nor does it grow progressively and steadily over time. More importantly, these studies revealed that fluctuations in hand use were not happening randomly or autonomously, rather, they occurred as a function of the successive locomotor skills that infants developed over the course of their first year. The remaining problem was to elucidate why patterns of hand use happen to fluctuate with infants' progression in locomotion. This was not clear because in both studies, infants were always reaching or retrieving objects from the box while they were fully supported in an infant seat; they were not crawling or walking while they were reaching and there was no balance threat while in the seat that could have prompted a change in manual response. Furthermore, the same seat was used for the same tasks across infants before they learned to walk, thus the postural support provided during reaching remained unchanged at all times. So, why was the emergence of crawling associated with a disappearance of preferred hand biases and the emergence of walking associated with a return to two-handed reaching?

An answer to these questions was suggested by the last piece of evidence from the study on walking and reaching (Corbetta & Bojczyk, 2002). We looked at how long the period of two-handed reaching lasted after infants began to walk independently. Interestingly, we found that the rate of two-handed reaching declined significantly a few weeks after infants began to lower their arms along the sides of their body during walking. In other words, coupling between arms

in reaching while sitting dissolved at about the same time infants began to decouple and lower their arms while walking -- the return and decline in two-handed reaching seemed to mirror the emergence of and subsequent progress in independent walking. It is this particular finding that suggested to us the mechanism that may have tied the observed developmental shifts in reaching with the development of infants' posture and locomotion.

To explain this mechanism, consider the following findings from the neuroscience literature. There are now several classic studies on brain plasticity showing that specific and novel sensory-motor experiences entail a functional reorganization of the sensory-motor cortex (Jenkins, Merzenich, Ochs, Allard, & Guic-Robles, 1990; Karni, Meyer, Rey-Hipolito, Jezzard, Adams, Turner, & Ungerleider, 1998; Kleim, Barbay, & Nudo, 1998; Merzenich & Jenkins, 1993; Merzenich, Allard & Jenkins, 1990; Petersen, Mier, Fiez, & Raichle, 1998, to cite a few). These studies are not limited to rats, but extend to non-human primates and human adults. A similar cortical reorganization was reported in human infants, in particular, following the emergence of hands-and-knees crawling (Bell & Fox, 1996). These cortical reorganizations are closely related to the task that is learned and practiced, and hence, to the specific limbs, body parts, and sensory organs that are used to achieve these tasks. Particularly relevant to our developmental story is the finding revealing that the acquisition of bimanual skills increases coupling of the cortical sensory-motor areas (Andres, Mima, Schulman, Dichgans, hallet, & Gerloff, 1999). Likewise, the use of one arm more than the other can entail a larger upper limb representation in the hemisphere contralateral to the hand used (Nudo, Milliken, Jenkins, & Merzenich, 1996). Finally and importantly, it has been shown that such experience-dependent neural reorganizations can, in turn, immediately shape motor performance (Dorris, Paré, Munoz, 2000). Thus, together, these studies show that there is a constant mapping between brain and

behavior as new sensory-motor skills are learned and practiced. Moreover, such mapping occurs as these tasks are performed intentionally, that is, with a goal in mind.

What do these data imply regarding the development of infant's hand preference? My colleagues and I hypothesized that a similar kind of mapping was taking place between reaching, crawling or walking, and the brain during critical periods of motor skill learning. When infants begin to crawl or walk, they develop a new behavior that was not present in their motor repertoire before. This new behavior involves using the body in a new way, by coordinating patterns of muscles differently, in order to achieve a new goal -- locomotion. When infants discover how to perform these new skills, they practice them a lot (Adolph & Berger, 2006). We believe it is the practice of these novel motor skills that temporarily transfers to reaching. Figures 1 and 2 illustrate how this transfer may have occurred. We describe the case of learning to crawl first (Figure 1). When infants are learning to crawl on hands-and-knees they need to figure out how to alternate hands and arms and legs to locomote. As they do so, both arms acquire an identical status or role since they are now both used alternately but equally to support and move the body around. Note that despite similarity of roles, the activities of the hands remain uncoupled since they are used in alternation. Our data on hand preference revealed that such uncoupled, alternated, but similar hand roles became the predominant mode of response in reaching, right at the time when infants began to practice hands-and-knees crawling (Corbetta & Thelen, 1999, 2002). Hand preference declined because infants were beginning to use either hand equally to reach for the target.

----- Insert Figure 1 about here -----

The same scenario can be applied to the transition to upright locomotion. When infants are learning to perform their first independent steps, they raise their arms in high guard and

couple them tightly to control their precarious balance during walking (Figure 2). Again, when this new skill emerges, infants practice it intensely for many days and weeks with their arms up and tightly coupled. We observed that infants who were beginning to walk also began to reach for objects at midline with two hands, suggesting that the tight arm coupling adopted and practiced during walking transferred to reaching. Furthermore, infants maintained this coupling as long as they were coupling their arms during walking. When infants improved upright balance control, lowered their arms and decoupled them, then two-handed reaching declined as well (Corbetta & Bojczyk, 2002).

---- Insert Figure 2 about here ----

Recently, we obtained further support for our interpretation on transfer of learning by studying the reaching patterns of two young infants who adopted unique forms of self-produced locomotion (Corbetta, Williams, & Snapp-Childs, 2006). One child who began to locomote by scooting on his buttocks while in a sitting posture, also began to couple his arms during reaching over the same period. The coupling in reaching occurred, presumably, as a result of the arm coupling performed to generate the scooting motion. Another infant, who preferred to crawl on his belly and dragged his body on the floor by using the same steady lateral pattern between hands and legs continued to maintain a strong right hand use for reaching. Unlike infants who alternated arms for crawling on hands-and-knees and displayed a disappearance in hand preference, this infant maintained a strong right bias as a result of never alternating arm movements during belly crawling.

Together, these examples on the development of hand preference in relation to the emergence of different forms of locomotion reveal that brain, body and mind maintain a tight match over time depending on the type of locomotor pattern adopted by the child. Furthermore,

this work reveals that developmental fluctuations in hand preference are intimately linked to the sensory-motor experiences that infants develop in the course of their first year. Thus, hand preference in early development is not necessarily a rigid, pre-established behavioral trait that is solely dictated by genes or an asymmetrical brain. Rather, early hand preference can be highly malleable and sensitive to the sensory-motor experiences and reorganizations of the postural system as infants learn to sit, crawl, and walk. Brain asymmetries may be subject to similar malleability. Finally, this work shows that even highly practiced skills, such as reaching at the end of the first year, which is performed with a goal in mind and with prior knowledge of the actions involved and characteristics of the target object, can be sensitive to other patterns that are developed and practiced by the body over the same developmental period. Here again, the brain and the mind do not simply command the body, but are constantly influenced by new patterns of activity and sensations received from the body.

## 5. Discussion

The work reviewed above shows that the body is not simply an instrument at the service of the mind or merely responding to the commands of the brain. The body possesses its own physical and biomechanical characteristics which need to be assembled, integrated, and mastered as part of the process of development and interaction with the environment. Discovering one's own body properties is a fundamental aspect of behavioral development as infants, children, and even adults engage in and learn new tasks. The brain is not foreign to this process, nor is it in greater command. Rather, the brain is involved in this process of behavioral learning as it fully partakes, in concert with the body and the environment, of the goal of achieving a particular task.

In that sense, body, brain, and environment are continuously meshed together in time and it is through changes in their mutual coupling that behavior and mind emerge and evolve in development.

All the examples I used in this chapter were on perceptual and motor development and relied on tasks that required specific actions from the body to be solved. These examples were chosen because they demonstrate how the body plays a role in the formation of behavior and learning. But what if the task did not involve bodily actions? One could argue that thinking does not always require the active participation of the body and that some forms of representation, mental images, or mental manipulations of concepts and symbols do not need the body to be evoked. Scientists can form theories, architects can envision buildings, physicists and mathematicians can reason about sophisticated laws. These are all activities that rely on very abstract mental processes and are using and manipulating abstract symbols. Can we think of those mental activities as disembodied? Here, I will address this question two ways: First, by discussing how the body and the brain are still connected and are still communicating with each other while these abstract forms of mental activities are taking place; and second, by expanding this argument to the developmental/learning domain and addressing the question of the origins of mind.

The brain and the body are always connected. The brain uninterruptedly “listens” to the body and is continuously tuned to sensations and feelings coming from the body even when the body lays still. Thus, even when we assume that the only brain activity actually taking place is happening in our mind, we still think in concert with our body. Some examples of self-generated mind activities, such as meditating or concentrating hard on a problem while sitting, are not independent from bodily sensations. In appearance, these mind activities do not require active

body involvement, yet, the brain, occupied by the thinking or concentrating process, still continues to receive information about posture, body orientation, or even background sounds from the surrounding. Any sound from the environment, any feeling or sensation arising from our body can suffice to disrupt the level of concentration or stream of thoughts during mental activity. The fact is that we learn throughout development to think with our body and within our body. If an uncomfortable posture is disrupting our strain of thoughts or meditative activity, we learn to find a better seat, better position, or better location so the constraints arising from our own body won't interrupt our mental efforts. What we practice and consider as "pure" mental activities, are in reality, mind activities intimately coupled with our body. Other, more individualized forms of mind-body coupling during the so-called "pure" thinking process can be seen in the frowning of the forehead, shaking of the foot, tapping of the pencil, or any other forms of activities that people engage into with their body to stimulate their thinking.

Recent research examples have provided beautiful illustrations of such mind and body coupling in tasks requiring perceptual judgments, recognition, or choice making activity, but no actual motor activity. They demonstrate that reasoning or cognitive processing in these tasks can be affected by physiological states, and can be intimately associated with underlying sensorimotor or neural activity patterns arising from prior individual experiences. Proffitt (see Proffitt, 2006, for a recent review of his work), for example, has performed a series of experiments asking adults to estimate perceptually the slant of hills. In most tasks, participants were standing at the bottom of a hill and were asked to visually judge the steepness of the hill while looking at it (no actual climbing was involved). Proffitt and his collaborators found that the explicit slant judgments of the participants were scaled to the effort they would have had to make to climb the hill, even though they were not asked to climb the hill. Furthermore, participants

overestimated the inclination of the slant if they were physically tired, or had a weight added on their shoulders at the time they were making their judgments. Proffitt's work clearly demonstrates that perception of the world and the cognitive interpretation that derives from it are embodied. Perceptual judgment tasks are not simply determined by the cognitive ability to analyze and interpret the physical characteristics of the surrounding (light conditions, geometry, perspectives, etc.) but are also influenced by the body, its physiological states, and potentials for action with the surrounding even though actions are not necessarily a requirement for the task.

Another example comes from the work of Knoblich and collaborators (see Knoblich & Sebanz, 2006, for a recent review) revealing how our basic understanding of the social world is embodied. Knoblich's argument relies on the mirror system (and mirror neurons in the brain) and shows that social cognition is often constructed on the recognition of patterns of perception-action of others, especially those patterns that are matching the patterns experienced by the observer. By identifying others people patterns of behaviors or actions and recognizing them as one's own, one can make clear predictions about other's actions. This mechanism of identification is considered by Knoblich as a crucial building block of social understanding and social interaction.

Finally, a last example comes from a recent study by Beilock & Holt (2007) showing how preferences and choices can be unconsciously driven by our motor system and prior experience. They asked expert and novice typists to simply choose between two neutral pairs of consonant letters that carried no meaning. One pair ("CJ"), if typed, would require the use of two fingers and would be easier to perform. The other pair ("FV"), on the other hand, would require the use of the same finger twice to be typed, which would be more likely to create interference. Note that there was no mention of typing in the study. The expert typists choose above chance

the pair that would have required two fingers to be typed, although, there was no explicit reasons to prefer that pair, whereas the novice typists showed no particular preference for one pair. These findings brought the authors to conclude that preference judgments, even of abstract, non emotionally charged stimuli, can be driven by covert sensorimotor experience.

Together, these examples reflect that some patterns of thinking, even if they do not require actual motor activity, are the product of body-mind coupling, and this body-mind coupling is deeply grounded in the sensory and motor experiences of the thinker.

This leads to the second point which deals with the developmental the origins of thought and embodied cognition. Where does the mind come from? How are thoughts generated? And how do memories or mental representations form? The answers to these questions are profoundly rooted in the developmental history of the individual, as infants, children, and adults act on and interact with their environment. Piaget (1967) considered mental representations, memories, and problem solving abilities as the product of prior internalized patterns of perceptions and actions. Dynamics systems approaches are compatible with the view that it is through the history of prior perceptions and actions in interaction with the task that mental forms such as memories, cognition, and patterns of behaviors emerge (see Spencer, this book; Smith, 2005). Many cognitive skills are, in fact, the product of a long developmental history involving sustained interactions between brain, body, and the environment through perception and action. The ability to count without needing our fingers or without needing pencil and paper, for instance, is the product of many repeated efforts at mapping the mind with the body pointing at targets or writing numbers. Language also is deeply grounded in the perceptual and motor system. Very early in development, infants fine-tune their hearing to sounds specific to their native language (Werker & Tees, 1984, 1992), and the production of sounds and speech develops as the child

learns to control and master the complex speech apparatus over time (Goffman, Heisler, & Chakraborty, 2006). Spatial representations have also been shown to form from perceiving and acting in the environment from a very early age (Campos, Anderson, Barbu-Roth, Hubbard, Hertenstein, & Witherington, 2000; Kermoian & Campos, 1988). To use yet another example, even highly skilled chess players, who can remember the position of each piece on the checkerboard and anticipate several potential moves ahead of time, have reached that level of mental performance after years of practice at the game grounded in perception and action. Each planned move reflects a potential for action that is deeply embodied. Highly skilled chess players have developed those forms of mental skills from hours of prior perceptions and actions involving the brain, the body, and the environment as the pieces were moved on the checkerboard and direct consequences of those particular moves were observed. These early skills then evolved to more sophisticated skills, where multiple moves and their outcomes could be envisioned by the player without direct action. In sum, it is hard to think of a disembodied mind, especially when we realize that all the senses the mind relies on to connect with the world are deeply embodied. Our senses of sight, touch, smell, hearing, and taste are intimately coupled with specific motor activities such as orienting the head, moving the fingers, activating our mouth and tongue, or turning the eyes to detect, capture, and encode information from the environment.

The embodied view sees the ability to develop abstract forms of thinking from the continuous body and mind mapping that takes place over developmental time. Just as infants manage to learn over the years to reach for objects in an endless number of varied situations without effort and without having to think hard of the dynamics of their movement, we have learned to think, reason, count, and generate solutions in our mind without needing to activate or

rely on our body. The fact that we can reach for objects seemingly “automatically” or think apparently without using our body are not evidence of a disembodied mind, but rather the indication that brain, body, and environment have reached a different level of coupling. In that sense, acquiring knowledge, becoming competent, remembering or developing social skills are not simply the product of a cognitive achievement; they are the product of a developmental real-time process of mutual interactions between brain, body, and environment.

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## Figure Captions

Figure 1: Process of transfer of learning related to the emergence of hands-and-knees crawling. When infants begin to self-locomote on their four limbs they learn to alternate arms and legs to move forward. This new alternated functional use of the arms for locomotion transfers to reaching, via brain functional reorganization, yielding a decline in preferred hand use.

Figure 2: Process of transfer of learning related to the emergence of upright locomotion. When infants begin to walk upright, they keep their upper arms coupled in a high guard position. This upper arm coupling performed during walking temporarily transfers to reaching, via brain functional reorganization, yielding an increase in coupled, two-handed responses during reaching.

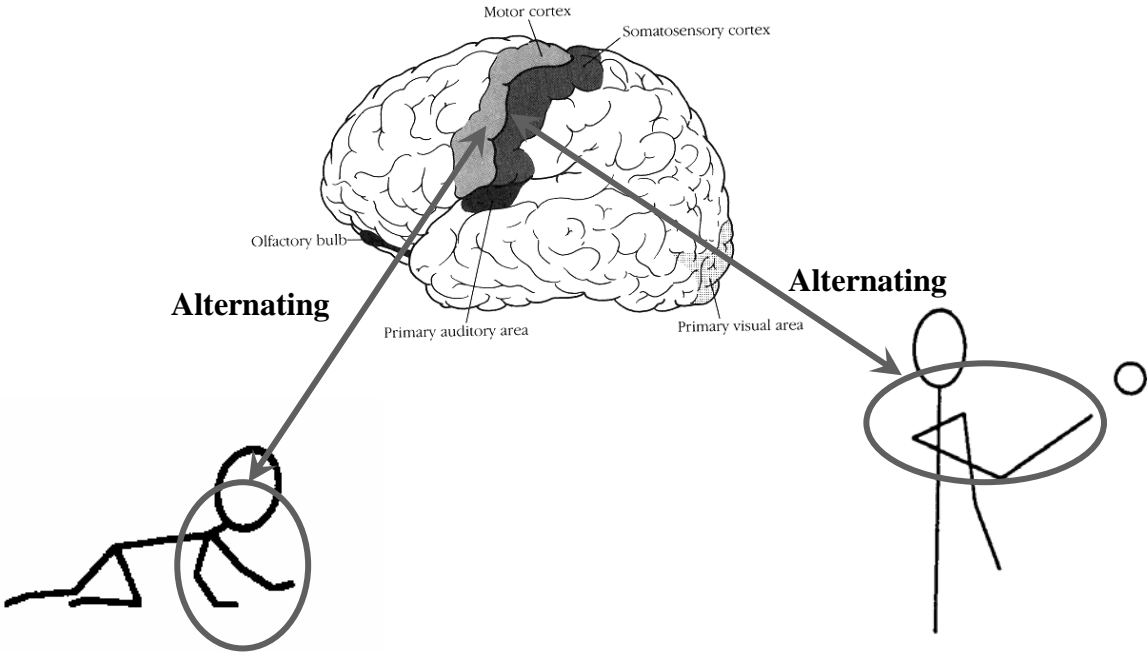


Figure 1

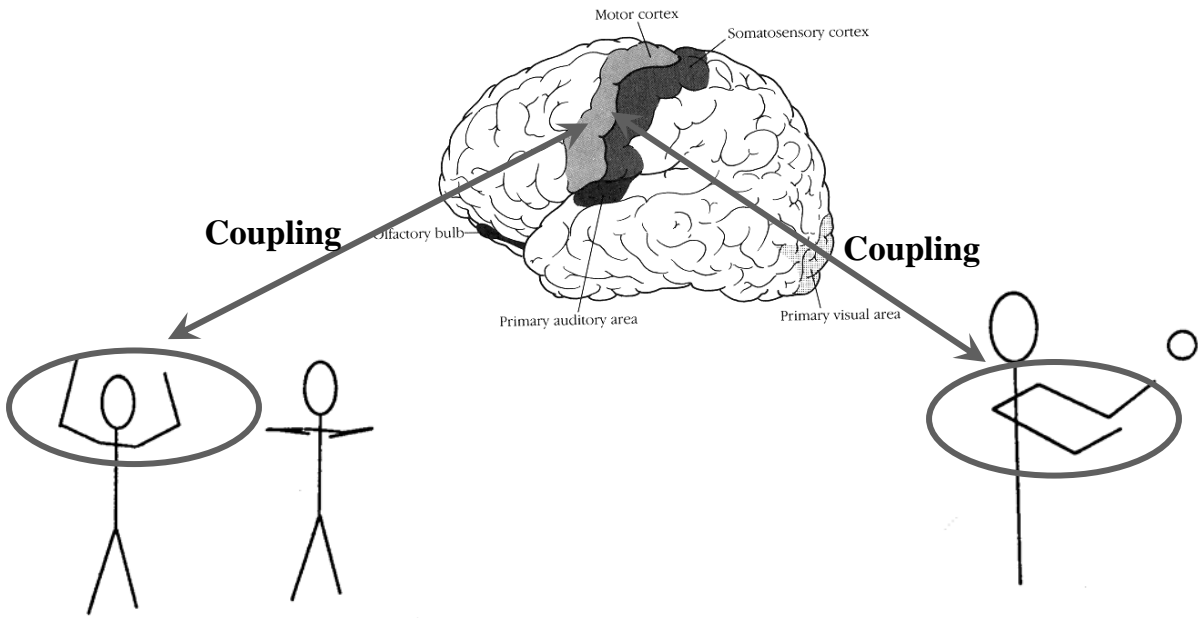


Figure 2