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The Embodied Origins of Infant Reaching: Implications for the Emergence of Eye-Hand Coordination

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This article reviews the literature on infant reaching, from past to present, to recount how our understanding of the emergence and development of this early goal-directed behavior has changed over the decades. We show that the still widely-accepted view, which considers the emergence and development of infant reaching as occurring primarily under the control of vision, is no longer sustainable. Increasing evidence suggests that the developmental origins of infant reaching is embodied. We discuss the implications of this alternative view for the development of eye-hand coordination and we propose a new scenario stressing the importance of the infant body-centered sensorimotor experiences in the months prior to the emergence of reaching as a possible critical step for the formation of eye-hand coordination.

Keywords: embodiment, vision, proprioception

The emergence of reaching around 3 to 5 months of age corresponds to a special moment in the infant's life where the gaze directed toward an object is accompanied by an arm extension also directed toward that same object. This moment, when gaze and arm intersect around a common aim, marks a significant transition in the early life of the infant and triggers a cascade of new behaviors in subsequent weeks and months. Objects that were predominantly examined visually prior to this moment can now be touched, explored manually, and eventually grasped and manipulated. In turn, those hand-object interactions allow infants to discover the rich physical features of objects (their texture, size, sound, shape, etc.); they help infants refine their actions on them and acquire a new sense of agency on the physical and social surroundings. Clearly, the emergence of reaching in the infant life opens the way to new and increasingly more sophisticated behaviors, such as in tool use mastery, and extends the infants' social exchanges with their caregivers and others.

Because the emergence of reaching marks such an important transition in the infant's early life, it has been studied extensively for nearly nine decades. Developmentalists have provided detailed reports of the steps and processes underlying its formation, and they have investigated how it improved over the first year of life. Over this extensive time span, one view has consistently predominated: that the emergence of reaching and its subsequent development are primarily guided by vision. This is still a widely-accepted interpretation, one that continues to be heralded in motor development textbooks despite discoveries in the past 25 years increasingly pointing toward a different process explanation of how infants are learning to reach.

The goal of this article is to review the literature on infant reaching, from past to present, in order to trace the history of how our understanding of the emergence and development of this early goal-directed behavior has changed over such an extended time span. Importantly, we aim to show that the predominant and still widely-accepted view, that the emergence and development of infant reaching occurs primarily under the control of vision, is no longer tenable. We present increasing evidence suggesting that the developmental origins of infant reaching is embodied. The general idea of "embodiment" entails that behaviors, thoughts, and emotions, traditionally considered the direct product of mind processes, are, in fact, deeply grounded in the history of sensorimotor experiences of the body in context (Varela, Thompson, & Rosch, 1992). These sensorimotor experiences fully participate in the process of mind formation and have been argued to play an important role in the formation of infants' behaviors (Corbetta, 2009; Smith & Gasser, 2005; Thelen, 2000). We discuss the implications of this embodied view for the development of eye-hand coordination in infancy.

The Origins of the "Visually-Guided" Reaching Hypothesis

The assumption that infants initially need vision to figure out how to bring their hand in contact with a wanted object dates back to the 1930s. Jean Piaget (1890–1986) was one of the first to provide detailed descriptions of the development of infant reaching based on the observation of his own children. In his pioneering book, *The Origins of Intelligence in Children*, Piaget (1936/1952) laid out the foundations of one of the longest held assumptions about learning to reach in infancy, namely, that infants need to look at their hands and the target alternately in order to progressively steer the hand closer to the desired target location. From Piaget's perspective, vision and action were not coordinated at birth. Thus, in order for reaching to emerge, vision and action needed to come together. Piaget interpreted each alternating glance between the hand and the object target as a strategy infants used to establish this fundamental eye-hand coordination. Systematic approximations of the position of the hand in relation to the position of the target and the subsequent visual guidance of the hand toward the target were assumed to be necessary steps for the development of an effective and more direct arm movement toward the target location. The term "visually-guided" was subsequently adopted to capture this early process of visual guidance of the hand to the target location.

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A number of developmental studies performed between 1960 and 1980 provided systematic support for this "visually-guided" hypothesis. White, Castle, and Held (1964) made detailed observations of the hand and arm behaviors of 34 institutionalized infants that they followed longitudinally from 1 to 6 months of age. White et al. identified eight stages of the development of what they called "visually-directed" reaching. They observed the first swipes at the object target at around 2 months of age (stage 3) and the first alternating glances between hand and object at around 3 months of age when hand and target were both within view (stage 4). On subsequent stages, they reported more alternating glances between hand and object until successful hand-object contacts occurred (stage 7, labeled "Piaget-type reach"). During these later stages, the researchers also documented behaviors such as clasping the hands at midline and clutching the clothing, particularly when infants were looking at the object presented at midline.

The "visually-guided" hypothesis continued to find support from other studies that used displacement prisms or mirrors to assess infants' reliance on the sight of their hand to contact the object target. Lasky (1977) devised a clever apparatus to examine the reaching and retrieving behavior of 50 infants aged between 2½ and 6½ months of age in conditions aimed at controlling the hand visibility during the reach. When a mirror was in place, infants could only see a virtual image of the object; the sight of their hands was occluded. When the mirror was replaced by a transparent plate, infants could see both the actual object and their hands. Lasky found that by 5½ months (when "visually-guided" reaching was considered established), infants' reaching and retrieval behaviors were impaired in the mirror condition when they could not see their hands, compared to the condition in which they could see their hands. Strangely enough, however, occlusion of the hand did not seem to affect the reaching performance of the younger infants. Overall, these infants contacted the object much less often than the 5½- and 6½-month-old infants, but when they did, they seemed to do so more often when they had no sight of their hand compared to when they had sight of their hand. Lasky could not quite reconcile this result with the "visually-guided" hypothesis and the response of the older infants.

In a different study, McDonnell (1975) examined the development of visually-guided reaching in 4- to 10-month-old infants while wearing 30 diopter displacement prisms. He also videotaped the reaching trajectories to analyze the hand paths to the object. He found that wearing the prisms only lead to a few target misses, compared to a no-prism condition. Further, he noticed that when wearing the prisms, infants' hand trajectories reflected a clear adaptation to the visual field displacement. The hand path, which was initially deviated (due to the prisms), was quickly followed by an abrupt correction in the direction of the object target. He concluded that these corrections were clear evidence that infants visually guided their reaching behavior because, to make such corrections, they had to see both their hand and the target. In a follow-up study, McDonnell and Abraham (1979) noticed that from 7 months old, infants' response adaptation to the displacing prisms was decreasing. Assuming the same reasoning, they concluded that the decrease in movement trajectory adaptation occurred because infants over 7 months old relied less on vision to guide their reaching movement to the target location, and therefore, they were less likely to correct the deviated direction of their movement (see also McDonnell, 1979).

One strong and very consistent finding in the developmental reaching literature relates to the infants' early reaching trajectories toward the object, particularly the fact that they are quite meandering and marked by numerous directional changes in hand path. This is not just a result of wearing displacing prisms. Infants at first have poor control of their arms and joints, and bringing their hand to an intended location is not an easy feat. Studies that began using cinematographic techniques (Mathew & Cook, 1990; von Hofsten, 1979, 1980; von Hofsten & Lindhagen, 1979) and later motion analysis systems (Fetters & Todd, 1987; von Hofsten, 1991) to capture infants' goal-directed arm trajectories toward a visible target further cemented the view that infants' early reaching attempts were visually guided. The numerous directional changes in hand path typical of infants' early reaching were interpreted as additional evidence of visual monitoring of the emerging goal-directed movement.

As infants made progress in eye-hand coordination and improved arm control, the number of trajectory corrections was observed to significantly decline. This qualitative change in movement trajectory was even corroborated by a number of later longitudinal studies that converged to show that infants' reaching trajectories started to become more straight and more direct roughly around 30–36 weeks of age (~7–8 months old) (Konczak, Borutta, Topka, & Dichgans, 1995; Thelen, Corbetta, & Spencer, 1996; von Hofsten, 1979, 1991). Further, it was observed that as the number of trajectory corrections diminished, the approach phase consisting of transporting the hand near the object target became longer, covered a greater distance—usually from movement start to object target—and was of greater duration. This qualitative change in the kinematics of the reach was now assumed to be under a different visual control process termed "visually-elicited" reaching (as opposed to "visually-guided" reaching).

The term "visually-elicited" was used to capture the fact that, in the second half of the first year of life, infants had established eye-hand coordination and only needed to look at the target—not their hand anymore—to make contact with the object. Bushnell (1985) even introduced a distinction associated with this developmental shift in eye-hand coordination that related to visuo-motor attention. In her review, she pointed to a number of studies that found that around 7 months old, infants also begin adjusting their hand orientation and hand shaping during the reach in anticipation of hand-object contact (Lockman, Ashmead, & Bushnell, 1984; Piéraut-Le Bonniec, 1985; von Hofsten & Fazel-Zandy, 1984). Bushnell's interpretation was that during the "visually-guided" period, infants did not show signs of movement preplanning as their hand approached the object because they were too busy monitoring their arm movement visually and, therefore, were unable to pay as much attention to the object's properties of shape and orientation. However, when "visually-guided" reaching begins to decline, the visual attention devoted to monitoring the hand could now be released to attend the physical characteristics of the object. Thus, during the "visually-elicited" developmental phase, infants could begin integrating the object physical properties into their goal-directed actions and pre-shape their hand movement in anticipation of grasping it.

The bulk of the work reviewed above forged the common held assumption that infant reaching developed in two phases corresponding to two distinct eye-hand coordination processes: an initial "visually-guided" phase spanning from 4 months to about 7–8 months of age followed by a "visually-elicited" phase starting around 7–8 months (see Figure 1). This two-phase developmental process based on visual guidance of the hand and change in visuo-motor attention has had a long-lasting impact on the field of infant reaching development.

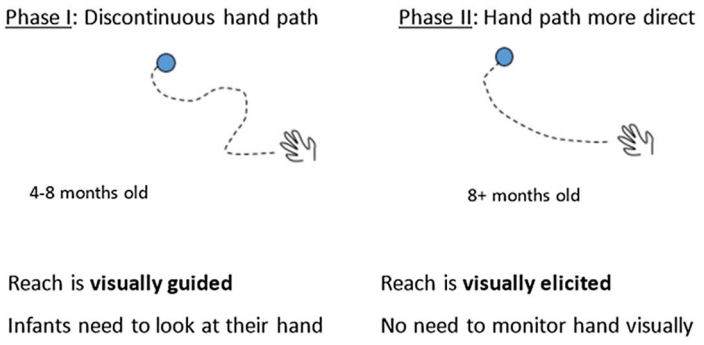

Figure 1 — Depiction of the two developmental phases typically describing the development of reaching in infancy. In phase 1, from 4 months to about 7–8 months old, infants' hand paths to the object are marked by several changes in movement direction. In phase 2, the path of the hand to the object becomes more direct. In early reaching studies, these two developmental phases were interpreted as reflecting different processes of infants' visual control of the hand during reaching.

Challenges to the "Visually-Guided" Hypothesis

In his pioneering book, Piaget (1936/1952) laid another long-lasting influence on the field of developmental psychology, namely, the idea that early mind formation rested on the early sensorimotor experiences of the child—an idea quite compatible with today's concept of embodied cognition. Nonetheless, in his explanation of the development of reaching in infancy, that specific aspect of his theory appeared to have been sidelined. His "visually-guided" explanation, endorsed by many, very much embraced a more traditional cognitive developmental process where the "eye" (the mind) was in charge of "guiding" the hand (the body). By the late 70s, however, some observations began contradicting the Piaget-type reach and the "visually-guided" hypothesis of infant reaching.

In a prism study aimed at examining the role of binocular convergence on the emergence of reaching in 18- to 32-week-old infants, von Hofsten (1977) failed to find the prisms' adaptation responses that had been reported by McDonnell (1975). Infants in his study often aimed at the virtual object defined by the converging prisms using ballistic movements and, thus, often missed intercepting the actual object. If he observed corrections in hand path trajectory, he reported that they occurred toward the end of the movement and he described these corrections as "time-consuming" (p. 143).

In a subsequent study, von Hofsten (1979) examined the development of the approach phase in 5 infants followed longitudinally from 15 to 36 weeks of age. The approach phase corresponds to the phase of the reaching movement that transports the hand from movement initiation to the vicinity of the object target. He observed that over the weeks, the movement paths to the target became shorter and straighter, and that the overall movement durations were becoming shorter as well. The number of changes in trajectory corrections also diminished as a function of age and was progressively replaced by an increasingly longer approach phase. By the time infants were 36 weeks of age, the approach phase, which corresponded to the first movement unit of the reach, represented nearly 90% of the hand trajectory to the object. If one focused solely on these changes in movement, these transitions in the kinematics of the approach phase would appear consistent with previous interpretations that infants shifted from a "visually-guided" to a "visually-elicited" reaching mode. However, in this study, von Hofsten (1979) used a video-recording camera directed at the infants' faces and reported never observing alternating glances between hand and object when movement corrections in reaching trajectory occurred. He reported that infants were consistently fixating on the object during the reach, not their hand, and concluded that his observations did not support the Piaget-type reach documented in earlier works (Piaget, 1936/1952; White et al., 1964).

Interestingly, as an alternative explanation for his findings, von Hofsten (1979) postulated "the existence of an undifferentiated visual-proprioceptive spatial system in the infant" (p. 176), raising an additional point of contention with Piaget who had conceived vision and action as separated schema from birth. According to von Hofsten (1979) and Bower (1974, 1976) in earlier work, vision and action initially functioned as a unitary system in infancy. Studies with newborns had observed that infants could generate ballistic or visually-triggered arm movement extensions without corrections very early on, but they often missed the target (Bower, Broughton, & Moore, 1970; Grenier, 1981; von Hofsten, 1982, 1984). To gain control of their arm and improve reaching accuracy, von Hofsten suggested, in agreement with Bower (1976), that infants needed to separate vision of the target in space from proprioception of their hand-arm coordination. This separation between vision and proprioception was assumed to occur around 24 weeks of age and was consistent with Lasky's (1977) findings in the mirror task where occlusion of the sight of the hand only had a disruptive effect on the reach of infants aged 5½ months and above. Presumably, before 5½ months of age, and because of this early visual-proprioceptive unitary system, infants performed visually-triggered reaches where the sight of the target and the feel of their arm were undifferentiated.

From that point on, researchers increasingly reported that infants sustained their visual fixations on the target and did not look at their hand during learning to reach. Von Hofsten (1984) himself went on to study the development of eye-hand coordination in infants during the 16–19 weeks preceding the emergence of reaching. He tracked the infants' forward arm extensions triggered in the direction of the object while monitoring infants' visual fixations to the target with a front video camera. During the earlier weeks, he found that synergistic arm extensions toward the target were not consistently occurring when the object was fixated. However, from about 10 weeks of age (~2 months old), he noticed a new type of response beginning to form. Infants' arm extensions in the direction of the target began to be accompanied by an opening of the hand during transport, and hand opening began to occur more frequently when the object was intensely fixated compared to arm extensions when the object was not fixated. Although contact with the target in that age range hardly occurred, he interpreted this developmental change in movement during intense target fixation as an adaptive response in preparation for the emergence of reaching.

Trevarthen (1974) described similar intense fixations at the objects around reaching onset and, much later, others did as well. Thelen et al. (1993) reported such intense fixations at the object target in four infants followed weekly around the transition to reaching. They wrote, "Typically, [the infants] fixated their gazes on the toy and did not look at their hands, which, in some cases, were moving rapidly and unpredictably around them" (p. 1087).

A study that more convincingly demonstrated the absence of "visually-guided" reaching in early infancy was performed by Clifton, Muir, Ashmead, and Clarkson (1993). They followed

seven infants at regular intervals between 6–25 weeks of age. At every session, infants were offered reaching trials of objects in ambient light, and they received reaching trials of glowing or sounding objects in a darkened room. The researchers found no significant age differences in the onsets of reaching and grasping between light conditions. Infants contacted the object first at 12.3 weeks and began grasping the objects at 16 weeks in the lit room. They began contacting and grasping the target at 11.9 weeks and 14.7 weeks, respectively, in the darkened room. Because infants could not see their hand in the dark, Clifton et al. inferred similar to von Hofsten (1979) that infants must have used proprioceptive cues with the sight or sound of the objects to direct their hand in the dark. They concluded that "visually-guided" reaching was a myth. Additionally, based on the findings of Clifton et al., it appeared that at reach onset, infants relied more on a "visually-elicited" strategy for reaching than a "visually-guided" one.

Although researchers nowadays agree that the "visually-guided" hypothesis is invalid, some debate remains as to whether young infants use some visual feedback during their reaches in ambient light. Two recent studies (Lee & Newell, 2012; Pogetti, Souza, Tudella, & Teixeira, 2013) found differences in reach onset and hand path when using an occluder to conceal vision of the arm during the approach phase of the reach (the sight of the hand at contact was visible). Lee and Newell (2012) reported an earlier reach onset when vision of the arm was not occluded, but did not find any differences in movement characteristics due to occlusion at 6 months and 1 year old. In contrast, Pogetti et al. (2013) found that, at 5 months old, occlusion of the arm led to fewer straight trajectories to the target compared to a nonoccluded arm condition. Pogetti et al. proposed a hybrid model whereby visual peripheral feedback of the hand could be used by the infants to guide their hand when available, but, if not available, infants would rely more on proprioceptive feedback than visual feedback to reach.

Toward an Embodied Origin of Learning to Reach

The idea that infants can rely on proprioceptive information to guide their reaching arm was out. From the 90s, additional studies reported that infants can reach in the dark, even on the sole basis of auditory inputs—that is, without sight of the target (Berthier & Carrico, 2010; Clifton, Rochat, Litovsky, & Perris, 1991; Clifton, Rochat, Robin, & Berthier, 1994). However, from this body of research, some questions still remained. First, if infants are not "visually-guiding" their reaches, how can one explain the highly discontinuous and numerous trajectory corrections typical of infants' early reaches? And, how do trajectories become more straightforward and smoother afterwards? Second, if infants look intensely at the object, and not at their hands, how does eye-hand coordination form in relation to proprioceptive control? How do infants figure out how to bring their hands where they hear or look in the first place? Here we address those questions and begin to point to evidence suggesting an embodied origin to infant reaching.

We start with the meandrous trajectories typical of young reachers. At about the same time Clifton et al. (1993) further demystified the "visually-guided" hypothesis, Thelen et al. (1993, 1996) investigated why infants' hand paths to the target when learning to reach were so indirect. They focused on the intrinsic dynamics of the target-directed movements generated by four infants followed weekly around the transition to reaching and until the end of their first year. By performing detailed kinematic and kinetic analyses of the arm movements, Thelen et al. (1993) found that during their first reaching attempts, infants did not quite know how to properly calibrate the speed of their articulated arm to the intended location of the target goal. Thelen et al. (1993) also observed that infants approached the reaching task with different levels of energy. Two infants, who were quite active in the few weeks before reach onset, generated fast movements toward the target when they produced their first reaches. The fast movements of their arms engendered large motion-dependent torques that dragged the arm away from the intended trajectory. To bring the arm back to where the target was located, those active infants had to produce multiple online corrections and actively stiffen their muscles to dampen those disrupting movement-dependent forces and steer the hand toward the target location.

Two other infants, who were calmer at reach onset, began to reach for the target in a surprisingly more mature-like fashion. The trajectories of their first reaching attempts appeared straighter and smoother. However, a few weeks later when they became active as well, they, too, lost control of their arm trajectory and began to produce indirect hand paths to the object. Thus, this study revealed that the discontinuous hand paths typical of the early reaching attempts were not related to a cognitive-like visual guidance of the hand. Rather, it was the product of a bottom-up, embodied process, whereby infants had to take into account those disruptive forces, generated by their own arm movements, to learn how to steer their hand to the target location. Gaining control of these intrinsic disruptive forces cannot be achieved visually; it entails practice and sensorimotor experience where body, brain, and mind work in concert (Corbetta, 2009).

Thelen et al. (1993, 1996) suggested that the way infants solved this motor control problem and learned to map their movements' dynamics to their intentions was through trial-and-error and exploration-and-selection processes (see also Thelen and Corbetta, 1994). By trying a wide range of movement speeds—some fast, some slow—infants were able to experience various movement dynamics, discover their effects on the reaching outcome, and progressively select the appropriate movement parameters leading to the smoother, more direct hand paths that are emerging later in the first year (see also Schlesinger, Parisi, and Langer, 2000). Thus, this work clearly demonstrated that, when beginning to reach, infants figure out how to bring their hand to a visible target, mainly by monitoring their hand path via proprioceptive control. This also explains why infants can perform goal-directed movements in the dark or without needing the sight of their hand (Berthier & Carrico, 2010; Clifton et al., 1991, 1993, 1994; Lasky, 1977; Lee & Newell, 2012; Wishart, Bower, & Dunkeld, 1978).

More recently, studies have continued to support the interpretation that learning to reach is a process of movement exploration and selection in relation to a goal (see Williams, Corbetta, and Cobb (2015) for a review). These studies also have highlighted the importance of haptic feedback (Corbetta, Williams, & Haynes, 2016; Schlesinger & Parisi, 2001) and contingent reinforcement (Berthier, Rosenstein, & Barto, 2005; Schlesinger et al., 2000; Williams & Corbetta, 2016; Williams, Corbetta, & Cobb, 2015; Williams, Corbetta, & Guan, 2015) in the formation and development of infant reaching. The Williams studies, specifically, were based on a 16-day intervention with infants who were demonstrably unable to reach for objects (on day 1, infants were 1 week shy of turning 3 months old). These infants discovered how to make contact with the target within days of the beginning of the study, and, once again, this research found that for reaching to emerge,

looking at the object was strong, while looking at the hands rarely occurred.

Let's turn now to the role of vision. If infants do not need to look at their hands to direct them to the target, then what is the role of vision at reach onset? Why the intense fixations of the object target prior to and during reaching onset? And, most importantly, if we go back to the original question, how do infants figure out how to coordinate vision and action in the first place when bringing their hand where they look? Is vision's role solely to locate the target object in space, or does it also serve some basic purpose for specifying movement direction (see, for example, Pogetti et al., 2013)? Is vision dictating to proprioception how to align the movement to a particular spatial location intensely attended?

In order to gain insights into those questions, Corbetta, Thurman, Wiener, Guan, and Williams (2014) began following infants weekly over the transition to reaching, while using an eye-tracker to capture infants' looking patterns at the objects. They presented preliminary findings based on three infants in a hypothesis and theory paper (Corbetta et al., 2014). They documented the infants' gaze at the object 5 weeks prior to reach onset, at reach onset, and 5 weeks after reach onset. They also compared the looking and reaching behaviors of those novice reachers with those of a more experienced 9-month-old infant group tested in the same conditions. In order to obtain enough eye-tracking data and to allow infants to scan the object targets sufficiently, they used a paradigm in which they held the object for 5 s at eye level, 60 cm from the infants (outside of their reaching space), and then they brought the object slowly within the infant's reach. For the whole 11-week period, they analyzed the distribution of gaze patterns on the object while the object was out of reach and they identified which part of the object infants' fixated the most. When infants began to reach, Corbetta et al. also identified which part of the object was first contacted by the hand. The results of these analyses are presented in Figure 2 for one of their objects shaped like a drumstick.

In the 5 weeks preceding reaching onset, infants distributed their looking patterns mostly between the head of the drumstick and the middle of the drumstick handle. After reach onset, however, the amount of looking at the head of the drumstick increased progressively, while the amount of looking at the middle of the handle decreased gradually. These developmental changes in looking distribution after reach onset were significant and followed the same trend in all three infants. Given these findings, one might predict a similar developmental pattern for reaching, where the hand contacting the target would shift progressively toward the head of the drumstick as the weeks passed. This expectation would be consistent with the common-held assumption that the eye somehow "tells" the hand where to go, but this is not what Corbetta et al. (2014) found. For reaching, they found that the area of the object that was contacted significantly more than the others across time was the head of the drumstick, and this was from the week of reach onset. No developmental changes were detected as per the area of first hand-object contact. Thus, over the 5 weeks following reach onset, the only developmental change observed was for the looking behavior. Further, and most unexpectedly, the looking and reaching behaviors of the three longitudinal infants at week 5 after reach onset were no different from those of the 9-month-old infants (see Figure 2). Arm trajectories to the target between the two groups were likely different, but as far as most-looked area and touched area, the infants with 5 weeks of reaching experience performed as the 9 month olds.

Corbetta et al. (2014) concluded that, contrary to expectations, it appeared that the longitudinal infants learned to progressively align vision to where they made contact and not the reverse. In other words, it looked as if the preferred area of hand-object contact increasingly dictated where infants should look predictively in order to increase the match between looking and object contact over developmental time. This developmental sequence from movement to eye is consistent with an embodied hypothesis. Note, however, that Corbetta et al. did not observe the same developmental trend with a plain rod object. In fact, they hardly found any significant results with the rod target, suggesting that looking and reaching might have interacted in different ways depending on the objects' features. Nonetheless, based on these preliminary findings, Corbetta et al. stipulated that by the time infants begin to reach, they must have acquired a strong embodied sense of how to move their arms in space using proprioceptive feedback. The idea that infants learn about their bodies and movements prior to reach onset has been proposed by some studies (Lobo & Galloway, 2013; Thomas, Karl, & Whishaw, 2015). We examine this idea next and discuss its implications for the emergence of eye-hand coordination.

Embodiment and its Implications for the Emergence of Eye-Hand Coordination

Many already have suggested that the origins of early reaching is grounded in the sensorimotor behaviors that newborns and infants perform in their first months of life (Bhat, Heathcock, & Galloway, 2005; Piaget, 1936/1952; von Hofsten, 1984, 1989; White et al., 1964). Neonates display some forms of behavioral responses indicating a tight coupling between perception and action (Meltzoff & Moore, 1977; van der Meer, 1997; von Hofsten, 1982), but here we suggest that this unified coupling does not persist for long.

Similar to what von Hofsten (1979) and Bower (1976) proposed, the visual and proprioceptive coupling, which accounts for the ballistic arm extensions of the newborn, needs to dissolve in order to set the path toward more organized and better controlled motor responses. Bower (1976) and von Hofsten (1979) thought that this decoupling was occurring around 24 months of age, but, in a later study, von Hofsten (1984) revealed that this decoupling occurred much earlier in the infant life. In his 1984 longitudinal study, he observed that neonates' arm extensions rapidly declined over the 2 months following birth. When arm extensions occurred, they were not linked significantly with target fixations, and the hand associated to the arm extension became more fisted around 7 weeks of age. It is only after this period that von Hofsten began to observe a progressive reopening of the hand during arm extension increasingly related to object fixations.

During those months preceding reach onset, infants also experience a large amount of time in their crib where arm and sight may not intersect very often. Infants may occasionally see one of their hands in their visual field when in the asymmetrical tonic reflex posture (Gesell & Ames, 1947), but infants' hands can also be elsewhere relative to their bodies and not always in line with their sight. While they do not see their hands all the time, they surely experience constantly the feel of their arm movement relative to their bodies, thereby discovering their peripersonal space.

Thomas et al. (2015) provided a very interesting report of the arm activities of infants during their first 6 months of life. They describe many incidences of these babies touching their bodies or grasping their clothing without ever looking at their hands. White et al. (1964) had documented such behaviors. Eventually, as

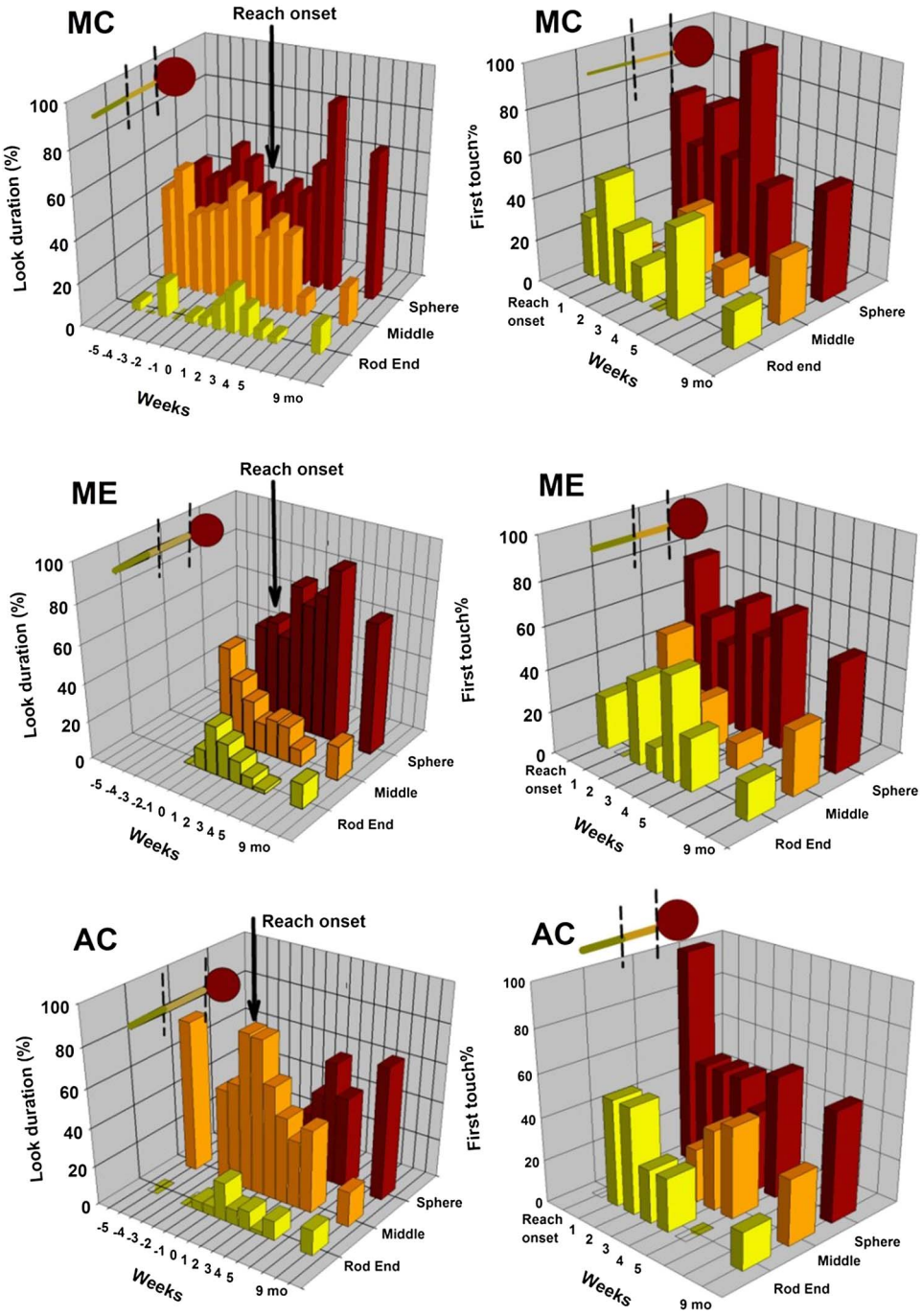

Figure 2 — Percent distributions of gaze patterns (left graphs) and areas of first hand contact on the object (right graphs) in three infants followed weekly from 5 weeks prior to reach onset (negative weeks), at reach onset (week 0), and 5 weeks after reach onset (positive weeks). Data from a group of 9-month-old infants are also displayed for the purpose of comparison. These 3D graphs show that the gazed areas for this drumstick object did not change significantly in the 5 weeks preceding reach onset. Changes in the gazed areas occurred after reach onset with increasing gaze at the head of the drum accompanied by a decrease in gaze at the drumstick handle. There were no developmental changes in the distributions of first hand contacts. Infants consistently reached more for the head of the drumstick from reach onset. Five weeks after reach onset, the gaze and first contact distributions of the longitudinal babies were no longer different from those of the 9-month-old infants. Reprinted from "Mapping the feel of the arm with the sight of the object: On the embodied origins of infant reaching," by D. Corbetta, S.L. Thurman, R. Wiener, Y., Guan, and J.L. Williams, 2014, *Frontiers in Psychology, 5*, p. 576. © 2014 Corbetta, Thurman, Wiener, Guan, and Williams.

vision matures, infants will begin discerning more things around them, but we postulate that the body-oriented motor activities they perform and visual inputs that infants receive while touching their bodies or moving their arms are unrelated to one another. Indeed, the feel of the arm and body, and visual input infants experience during this pre-reaching period, happen in very different dimensional spaces. While arm movements occur in a space close to the body, information gathered visually can come from much farther distances, clearly encompassing the infant's peripersonal space. Infants can direct their gaze to a mobile out of reach, to a poster on

a distant wall, or even to the bars of their crib, or to any number of other things in the room that are out of reach. We posit that the embodied sensorimotor experiences infants acquire before reach onset take place during those periods of spontaneous arm movements combined with haptic feedback received from touching their own bodies. These sensorimotor experiences provide to the infants a sense of their arms in space, a necessary condition for proprioceptively-controlled reaching. The infants' visual perceptions, on the other hand, occur in a much wider dimensional space. Thus, early proprioceptive and visual experiences may not be scaled to one another. Reaching onset would correspond to the first instance in the infant's life where these two spaces—the feel of the arm and vision of the target—would intersect.

We speculate that in the Corbetta et al. (2014) study, infants aligned vision to their reach, and not the reverse, because vision is the modality that infants need to scale down to the extensive body-centered proprioceptive experience they have acquired before reach onset. Bringing the hand to a specified "looked" location may be a new task, but if it happens once, the chance of it being repeated can be high because of infants' implicit proprioceptive "knowledge" of their arm movements. As discussed in Williams, Corbetta, and Cobb (2015), the first contact with the target, while fixating on it intensively, may well occur coincidentally; the infants flailing their arms happen to touch the target by chance. That first chance contact, however, may suffice to trigger a chain reaction, whereby the infants try to reproduce this effect, and data show they surely do (Williams & Corbetta, 2016; Williams, Corbetta, & Guan, 2015). This is why we see the origins of reaching as embodied. The sensorimotor experience acquired during months before reach onset is what infants rely on to generate their initial target-oriented movements (Clifton et al., 1993; Lasky, 1977). The next task they need to solve to achieve eye-hand coordination is to scale down and calibrate their visual experience to the proximal space of the infant's action. This may occur within a few weeks as suggested by Corbetta et al. (2014). From that point on, vision becomes predictive and goal-directed responses become visually-elicited.

Clearly, future studies are needed to examine our scenario and better understand how infants achieve this important milestone. In an attempt to assess the embodied origins of infant reaching, we are currently following the arm movements, body-oriented touch, and gaze behavior of young infants followed longitudinally from 3 weeks of age up to reach onset. It is our hope that this work in progress will offer additional clues to the proposed scenario and the development of eye-hand coordination in infancy.

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