

Developmental Origins of Biological Motion Perception

Willem E. Frankenhuys,

H. Clark Barrett, &

Scott P. Johnson

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AUTHOR INFORMATION:

Willem E. Frankenhuys

UCLA Department of Anthropology

341 Haines Hall, Box 951553

Los Angeles, CA 90095–1553, USA

wfrankenhuys@gmail.com

H. Clark Barrett

UCLA Department of Anthropology

341 Haines Hall, Box 951553

Los Angeles, CA 90095–1553, USA

barrett@anthro.ucla.edu

Scott P. Johnson

UCLA Department of Psychology

1285 Franz Hall, Box 951563

Los Angeles, CA 90095–1563, USA

scott.johnson@ucla.edu

Introduction

“We don’t simply see, we look.”

—Eleanor J. Gibson, 1988

The perception of biological motion is a central theme in developmental psychology. One reason is that from the moment newborns enter the world they have a special affinity for motion. For instance, while the neonate’s visual field ranges only 15–20° to either side for static stimuli (when the head is still), it can be wider and the distance greater for moving objects (Tronick, 1972). Moreover, studies have shown that infants’ visual attention is especially attuned to biological motion (e.g., Bertenthal, 1993; Fox & McDaniel, 1982; Gergely, Nádasdy, Csibra, & Biró, 1995; Rochat, Morgan, & Carpenter, 1997; Simion, Regolin, & Bulf, 2008). For example, newborns are capable of fixating on moving face-like stimuli in the first hour after birth, and they preferentially track faces over other stimuli that are controlled for such characteristics as luminance and complexity (Johnson, Dziurawich, Ellis, & Morton, 1991). Further, when neonates are presented with two displays side-by-side—one depicting a point-light display of an animal walking and the other non-biological motion—they tend to navigate their gaze towards the biological motion (Simion et al., 2008).

Outline of chapter. The current chapter describes the development of biological motion perception. In doing so, it will highlight not only the initial abilities that infants

come into the world with, but also how these abilities develop over the first years.

Several ideas will permeate the chapter, albeit in a latent fashion. The first is that babies are not little adults, but instead are adapted to their particular life-stage. For example, the fact that newborns have a narrower visual field than adults *might* be a “limitation” of their perceptual systems, but it may also help them orient towards those things in the world that matter to *them*, such as their caregiver (see also Turkewitz & Kenny, 1982). A second theme is that, instead of being the passive recipients of external influences, infants, from birth, are active agents that scan their environments and *select* the objects and events they attend to. To use Eleanor Gibson’s words, infants do not see; they look (1988). Thirdly, in the domain of biological motion perception, there are many interesting methodological overlaps between adult and infant vision research. The methods employed in infant studies (e.g., point-light displays) are sometimes borrowed from adult vision research, but infant researchers have advanced their technologies in ways that are likely of interest to adult vision scientists. The present chapter reflects the fruits of crosstalk that has occurred so far.

The chapter is organized along a set of different perceptual and inferential tasks that infants face, focusing on their first fifteen months. Naturally, these challenges dovetail with some of the major themes and questions in the study of biological motion perception in infancy. Still, the specific carving we chose is, inevitably, subjective and incomplete. Our aim is not to provide a comprehensive review of the literature, but instead to give the reader a taste of the exciting research that is being done on this subject. The chapter is divided into four sections. The first three sections each deal with one topic in the field, focusing primarily on empirical results. These topics are: (1)

Developmental Foundations of Visual Perception, (2) Detecting Animate using Motion, and (3) Inferring Goals and Other Mental States from Motion Dynamics. The fourth section is a discussion that will offer a summary of the findings presented in the earlier sections and point to some interesting relations between them.

Before beginning, a note on the term “biological motion.” Sometimes when this term is used in the psychological literature, it has a very specific meaning, such as motion that is perceivable from point-light displays. While we do wish to include that specific meaning in our use of the term, we intend to use the term much more broadly, to include any motion that is produced by biological entities, i.e., animate objects. In the chapter, we will consider various aspects of biological motion perception, including point-light displays, but also the many other ways that living things move.

Section 1: Developmental Foundations of Visual Perception

“The oculomotor system—unlike other motor systems—approximates its mature state several months after birth. The infant exercises this system every day from birth on. This makes vision one of the most important channels through which infants learn about the world surrounding them.”

—Sabine Hunnius and Reint H. Geuze, 2004

Our subjective experience of the world is framed in terms of objects and events, parsed from the ongoing flow of perceptual input. Especially important are events

involving animate objects, including our fellow humans, and it seems sensible that infants would be able early on to make such distinctions and identify their conspecifics (e.g., Rakison & Poulin-Dubois, 2001). Notably, infants inhabit the same world as do adults, with the same kinds of sensory information in the surrounding environment. But do infants have the same access to perceptual input as do adults, and do they have the same interpretation of the information that specifies a person or other animate being? We will address these questions in this section of the chapter by characterizing the perceptual and cognitive skills infants bring to bear on the task of perceiving objects and events, and by outlining the kinds of developmental change that have been investigated by researchers. In later sections we will consider the kinds of motion infants appear to detect that adults interpret as biological in nature. To anticipate, very young infants’ visual systems are well equipped to detect the sensory input relevant to object and event perception. Yet many aspects of person perception are not available to infants, due, for example, to restrictions in the ability to integrate information across space and time and other cognitive limitations. These cognitive limitations are overcome with experience and maturation.

Object and event perception comprises detection of the meaningful units in the flow of perceptual information, and integration of these units into a coherent structure. It is not necessarily easy to define some of these terms, such as “meaningful units,” because what is meaningful to one observer may be unintelligible to another (e.g., when listening to a foreign language), and what constitutes a unit may vary across observers as well. Such caveats are especially well taken when considering visual perception in infancy, where behavioral measures may be related to cognitive constructs indirectly and it may

be difficult to discern which aspects of any particular stimulus are most salient. We will consider the nature of the visual environment itself, therefore, and how it might appear to infants.

The visual environment. Vision operates over both space and time. Objects generally occupy fixed locations or move on predictable trajectories, and events are by definition temporal in nature. Visual input starts with the eyes, of course, which are movable such that visual attention can be directed toward relevant targets in the world, and the observer is generally free to move around, which enables exploration and discovery of new visual features unavailable from previous vantage points (Gibson, 1979). Young infants lack the capacity for free movement of the body, but the oculomotor (eye movement) system is largely functional shortly after birth and infants make good use of it to learn about the world.

Accurate perception of objects—their spatial layout, physical extent, typical behavior, and so on—is required for the optimal functionality of such action systems as reaching and locomotion which reach maturity after many aspects of object perception have emerged, early in the first year after birth. To perceive objects accurately, the infant must (a) make effective use of her visual attention, (b) detect the unity, boundaries, and persistence of objects, and (c) categorize stimuli as similar or dissimilar, as appropriate. Each of these is discussed in turn.

Visual attention. The most common type of volitional eye movement is the saccade, a quick shift of fixation from one location to another. A second type is smooth pursuit, the tracking of small moving targets. Saccades are functional from birth and

smooth pursuit emerges over the first several postnatal months; both undergo rapid developments prior to the first year (Johnson, 2001). Adults move their eyes, on average, 2-3 times per second in everyday tasks such as scanning visual scenes and reading (Fischer & Weber, 1993; Rayner, 1998). Infants also scan visual displays actively and saccade patterns become more organized and systematic across the first several months after birth (Johnson, Slemmer, & Amso, 2004). Neural theories of these changes propose that improvements in visual attention are due to maturation of visual circuits in the brain (e.g., Johnson, 1990; Schiller, 1998). Cognitive theories stress the infant's ability to learn from information in the environment to modify scanning, enabling increasingly efficient information extraction (e.g., Johnson, Amso, and Slemmer, 2003). In the real world, events are often complex and appropriate behaviors may be difficult for the infant to achieve. Little is known about how infants go about determining how to direct their gaze under such conditions, but it is becoming increasingly clear, with the advent of new technologies to record eye movements in infants, that young infants often focus on features of the world that may not be very informative (Frank, Vul, & Johnson, 2009). Nevertheless, under controlled circumstances in the laboratory, infants provide evidence of rapid developments in object, face, and motion perception, and these will be discussed in the following sections.

Object perception. There is more to the surrounding environment than what can be seen, because the full extent of objects is unseen from any single vantage point. A perennial question of developmental science concerns how infants, with relatively little experience in the world, may construe the visual world as fragments, as objects, or perhaps as something in between. Piaget (1952) famously described a series of errors

produced by infants as they attempted to search for an object concealed among a single or multiple potential hiding places (including the “A-not-B” error), and concluded that early in the first year after birth, infants experience the world as consisting of “sensorial images” that have no substance or volume. More recent research has provided mixed support for these findings and Piaget’s theory more broadly, mainly in terms of precisely *how* object perception develops.

Newborn infants have been tested for *unity perception*—perception of partly hidden objects as complete despite occlusion—and most evidence to date indicates that they seem to construe partly occluded objects as parts only, not as wholes (Slater, Morison, Somers, Mattock, Brown, & Taylor, 1990, but see Valenza, Leo, Gava, & Simion, 2006). Two-month-olds perceive unity in partial occlusion displays under certain circumstances (e.g., if the occluder is relatively small and the visible parts closer together), and by 4 months, unity perception is more robust (Johnson, 2004). A similar developmental pattern holds for infants’ perception of objects that move on a visible trajectory, become occluded by a screen, and subsequently re-emerge. Two-month-olds did not perceive a partly occluded trajectory as continuous across occlusion, but under some circumstances, such as a narrow occluder, 4-month-olds did perceive trajectory continuity, and even older infants (6-month-olds) were able to perceive continuity even in a wide-occluder display (Johnson, Bremner, Slater, Mason, Foster, & Cheshire, 2003). A “parts-to-whole” developmental progression, therefore, is a suitable characterization of young infants’ object perception.

Face perception. Under laboratory conditions, newborns and young infants prefer to look at schematic faces and face-like forms relative to control stimuli (e.g., Goren,

Sarty, & Wu, 1975), a fact that has motivated a large number of experiments attempting to pin down the precise nature of the preference. Explanations for the face preference have ranged from a representation present at birth for facial structure that guides visual attention (Johnson & Morton, 1991; Morton & Johnson, 1991), to the opposite view, an set of general-purpose visual biases present at birth that guide attention toward stimuli that happen to match characteristics of human faces (Valenza, Simion, Macchi Cassia, & Umiltà, 1996). A recent study by Sugita (2008) found that monkeys, when deprived from exposure to faces in their first 6-24 months, showed a preference for faces over control stimuli, consistent with the existence of a representation that is present at birth. General-purpose visual biases may include a preference for visual stimuli that are “top heavy” with more detail in the upper region than the lower, and a preference for stimuli that move, especially in tandem with sounds with which infants are familiar from prenatal exposure—the human voice. In complex visual displays, this face preference is overshadowed by the tendency to look at low-level visual salience—bright colors, high contrast, and motion—until some time after 6 months (Frank et al., 2009). This implies that infants may indeed be prepared to detect and identify conspecifics by examining their faces, but faces are not necessarily the most interesting aspects of the visual scenes infants encounter.

Perceiving faces is like perceiving objects in an important respect: Infants initially seem to process faces on the basis of individual features and only later as coherent wholes. In face recognition experiments with adults, observers view upright or inverted faces, followed by pairs of faces, one new and one from the training set, and attempt to identify which was seen previously. Recognition was near ceiling when faces

were upright, but when faces were inverted, performance was relatively poor—the *inversion effect* (Yin, 1969). This may reflect a difference in processing “strategies” when viewing upright vs. inverted faces. When faces are upright, they are processed in terms of both the individual features and the spatial relations among features, but when inverted, these relations are more difficult to access, forcing greater reliance on only a single source of information for recognition—the features—and thus impairing performance. Carey and Diamond (1977) found that young children do not show the inversion effect, leading to the suggestion that young children process faces strictly as collections of features. However, more recent evidence has shown an inversion effect in infants’ face recognition, suggesting the part-to-whole shift in processing faces occurs early in life (Rose, Jankowski, & Feldman, 2008; Younger, 1992).

Motion perception. Moving objects and edges attract infants’ attention from birth (Slater, 1995), although discrimination of certain complex patterns of motion takes several months to develop. *Motion direction discrimination*, for example, is the ability to detect differences in motion patterns within random dot displays, and it has been thought to emerge between 6 and 8 weeks after birth (Wattam-Bell, 1996). This developmental timing is consistent with that of oculomotor smooth pursuit, leading to speculation that maturation of these two skills relies on a common cortical substrate (Johnson, 1990). The attention-attracting properties of motion have been thought to serve as an important means by which object and person perception can proceed during development, because those things in the environment that move will tend to draw the infant’s gaze, and more attention toward these particular parts of the visual scene can facilitate learning about them (Blake & Shiffrar, 2007; Johnson, 2005; Kaiser & Shiffrar, this volume). Recent

findings of a preference for biological motion at birth suggest that infants are prepared to process conspecific-relevant motion information even in the absence of learning from experience observing the visual environment (Simion et al., 2008; Sugita, 2008).

Summary. Infants are born with a functional visual system, and are well prepared from birth to attend to and learn about objects, people, and events in the visual environment. A developmental progression from processing complex visual stimuli principally on the basis of individual features and parts toward perception of structured wholes is seen in a variety of object and face perception experiments. Infants initially appear to process simple isolated units, and subsequently integrate those simple units into higher-order patterns. Nevertheless, some complex visual patterns, such as schematic faces and biological motion, attract newborn infants’ attention, suggesting a preparedness to process socially-relevant information in the absence of extensive visual experience or learning.

Section 2: Detecting Animates using Motion

“If the doors of perception were cleansed every thing would appear to man as it is, infinite.”

—William Blake, *The Marriage of Heaven and Hell*, 1790

As mentioned, infants are sensitive to biological motion from a very young age (Bertenthal, 1993; Fox & McDaniel, 1982), perhaps even as early as birth (Simion et al., 2008). In this section, we ask: What are the properties of biological motion that infants

are sensitive to? We focus on a seminal body of work that used point-light displays—i.e., arrays of point-lights moving as if attached to the major joints and head of a human or animal walking (Johansson, 1973, 1977; Cutting, this volume)—to explore the properties of biological motion that infants attend to, and we also discuss some recent studies on infants' perception of the human body morphology.

Upright vs. random. Fox and McDaniel (1982) conducted the first studies of biological motion perception in infants. In a classical paper, they examined whether 2-, 4-, and 6-month-old infants discriminated a point-light display of an upright human walking from a point-light display in which the lights were moving independently, each one in a randomly determined direction (random). The displays were presented side-by-side, and 50% looking at each display would indicate that the infants did not discriminate. The results showed that the 4- and 6-month-old infants looked longer at the upright walker than the random display, while the 2-month-old infants looked equally long at both displays. This was the first study to suggest that infants as young as 4-month-old are sensitive to biological motion.

Upright vs. inverted. Since the motions were stochastically generated in the random display, the absolute motion properties of the point-lights in the upright and random display were not identical. Therefore, Fox and McDaniel (1982) conducted a second study in which they presented 4- and 6-month-old infants with a display depicting a human walking (upright) and another display depicting the same point-light walker inverted 180° (inverted). These images differed *only* in their orientation. The results showed that both 4- and 6-month-old infants attended more to the upright than the inverted walker, suggesting that infants also use orientation in selecting the objects of

their visual attention.

A potential problem with presenting upright versus inverted displays is that infants may not look equally at all portions of the screen (Bertenthal, Proffitt, & Cutting, 1984)—for instance, because looking at the top requires more effort in terms of lifting one's head. This would not be a problem if the absolute amount of motion were equal across all portions of the screen; however, point-light walkers tend to exhibit more motion in the leg-and-feet region (two limbs) compared to the head region (one limb). Therefore, infants might have attended more to the upright over the inverted walker, not because they have an orientation-specific preference for biological motion, but because they were drawn to the more *perceived* absolute motion in the upright display.

Upright vs. scrambled. Bertenthal et al. (1984) designed a study that addressed this potential confound. They presented 3- and 5-month-old infants with an upright point-light walker (upright), and a display in which the point-lights moved identically to the upright display, except that their spatial locations were scrambled (scrambled). The amount of absolute motion at the top and the bottom region was made comparable in the upright and the scrambled display. Therefore, both the amount of *actual* and *perceived* absolute motion were the same in the upright and scrambled display, and any effect would only be attributable to infants' ability to discriminate based on configural properties (i.e., how the parts move in relation to each other). To adults, the movements of scrambled point-lights may appear as “an abstract machine squirming cyclically across the screen ... [or] something akin to a swarm of mechanical bees” (Cutting, 1981, p. 81).

Habituation. To test infants' discrimination of upright vs. scrambled displays,

Bertenthal et al. (1984) used a habituation method. This method stems from the original work of Robert Fantz (1964). Fantz showed that when infants are presented the same picture over and over their looking times decrease (*habituation*), and he also showed that if the infants then observe a novel stimulus during the test phase their looking times increase again (*dishabituation*). However, because infants may have very different habituation profiles, depending on such factors as age, mood, sex, temperament, later researchers developed an infant-control habituation paradigm (Cohen, 1972, 1973; Horowitz, Paden, Bhana, & Self, 1972); here, the habituation criterion is set *per* infant, usually at “the point when total looking on three consecutive trials sums to no more than 50% of the total looking on the first three trials” (Bertenthal et al., 1984, p. 219). Trials begin when the baby starts looking at the display and end when it looks away (e.g., for 2 seconds), so trial duration is under the infants’ control (for more details, see Bertenthal, Haith, & Campos, 1983).

Using infant-control habituation, Bertenthal et al. (1984) could show that both 3- and 5-month-old infants discriminated the upright and the scrambled point-light walker. The study also showed that such discrimination did *not* occur when the infants were presented with an inverted point-light walker pitted against an inverted scrambled display (*inversion effect*), nor with a static picture of an upright point-light walker versus a static scrambled display (i.e., static morphological differences had no effect). That 3- and 5-month-olds discriminated the standard point-light walker from the scrambled point-light walker *only* when the point-light walker was upright *and* in motion, suggests that young infants are sensitive to the configural properties of biological motion, but only in a specific orientation (for a discussion of such inversion effects in adults, see Troje &

Chang, this volume).

Perception of body shape. Developmental psychologists have recently also begun to explore whether biological motion also plays a critical role in infants’ perception of body *morphology*. Slaughter, Heron, and Sim (2002) presented 12-, 15- and 18-month-olds with two static images side-by-side, one depicting a typical human body shape and the other a scrambled human body—some body parts (e.g., the arms) were interchanged with other body parts (e.g., the legs). If infants are attuned to the typical body shape, then we expect them to respond differently to typical and scrambled bodies. However, while 18-month-old infants did look longer at the scrambled bodies, 12- and 15-month-olds divided their attention equally among the images, suggesting that either they did not discriminate, or that they did not have a preference for one image over the other. A follow-up experiment confirmed that younger infants were not able to distinguish between the images (Slaughter & Heron, 2004). This result is noteworthy considering that infants of this age do exhibit a preference for configural properties in faces (Johnson & Morton, 1991; Morton & Johnson, 1991).

However, when do infants begin to recognize the morphology of the human body *when body parts are moving*? Christie and Slaughter (2010) presented 6-, 9-, and 12-month-old infants with typical body shapes with moving body parts (i.e., the head moved from left right, the arms and legs up and down) until habituation occurred, and measured whether infants recovered interest to animations in which the body parts were misplaced (scrambled). The results showed that, with motion, infants as young as 9-month-old, but no younger, distinguished the typical body morphology from the scrambled body morphology. Given 9-month-olds inability to distinguish typical and scrambled bodies

with static images, the latter result provides evidence that motion can facilitate body recognition in young infants (for an ERP study with younger infants, see Gliga, & Dehaene-Lambertz, 2005).

The role of motor development on perception of others' actions. There is a growing body of evidence suggesting that as infants come to control their own body movements, they begin to identify actions in themselves and others as familiar. Schmuckler and Fairhall (2001), for example, found that 5- and 7-month-old infants looked longer at point-light versions of another infants' legs in motion than their own (viewed in real time), implying sensitivity to the visual-proprioceptive links available when they simultaneously see and feel information for self-produced movement. Similarly, perception of goal-directedness in events consisting of a hand reaching for one of two objects (presumably reflecting a desire for the reached-for object) was facilitated in 3-month-old infants by experience manipulating objects (Sommerville, Woodward, & Needham, 2005). Under typical circumstances 3-month-olds are incapable of skilled reaching for and grasping of objects, but this can be accelerated by providing infants with "sticky mittens" covered in Velcro; the Velcro sticks to specially prepared toys in front of the infant, thereby providing the infant with opportunities to interact with toys. Finally, Sanefuji, Ohgami, Hashiya (2008) reported that infants who recently began either crawling or walking preferred to look at point light versions of crawling or walking human figures vs. figures engaged in walking or crawling, respectively. These looking patterns were not the result of experience with the chosen means of locomotion, because walking infants, of course, tended to have more experience crawling than those infants who had just begun to crawl. Instead, it seems likely that as infants engage with a

particular motor activity, they begin to recognize the equivalence of their own behaviors and those of individuals with whom they come in contact.

It is also interesting to look at the performance of older age groups in recognition tasks of biological motion. Pavlova, Krägeloh-Mann, Sokolov, and Birbaumer (2001) presented 3- to 5-year-old children with static and moving point-light displays of a walking person, a walking dog, a running dog, and a bird. The static stimuli consisted of four snapshots of the corresponding moving display. Participants viewed one display at a time and stated verbally what animal they saw. The results indicated that recognition was above chance for the dynamic displays in all age groups, although there was a clear developmental progression between the ages 3 to 5, with 5-year-olds reaching the ceiling level of 80-100% accuracy. By contrast, static images were not recognized in any of the age groups. These results underline the crucial contribution of motion dynamics in the recognition of animates.

Specificity of biological motion sensitivity. Infants can detect biological motion early in life, preferring upright from scrambled and inverted displays, and use motion to recognize body morphology. We now turn to the question: Precisely what are the properties of biological motion that infants are sensitive to? Bertenthal et al. (1984) argued with respect to point-light displays that there is "an indefinite number of possible configurations that could be perceived depending upon what relative motions are extracted" (p. 227). In other words, if the perceptual systems were unconstrained, the number of interpretations of incoming sense data would, at least in principle, be limitless—hence Blake's quote at the top of this section. What are the properties, amidst the "blooming, buzzing confusion" of the outside world (James, 1890), which draw the

attention of young infants to biological motion?

In evolutionary terms, one can ask two distinct kinds of questions here: what were the sources of selection that shaped a particular mechanism ancestrally, and what are the properties of the resulting mechanisms that make them sensitive to certain kinds of inputs? Evolutionary psychologists call these questions of proper and actual domain, respectively (Barrett, 2009). In the case of infants' sensitivity to biological motion one can ask: what kinds of biological objects selected for this ability (proper domain)? Was it just other humans, or particular kinds of humans (e.g., mother), or did it include things like animals as well? The answer depends on the kinds of challenges infants faced and how these impacted fitness, e.g., detecting the presence of mom, detecting the presence of dangerous animals, and the like. The kinds of mechanisms these selection pressures shaped, and *how* they pick out their inputs, is in turn a different question (actual domain). The specificity of the input criteria will depend on factors related to signal detection, such as the costs of different kinds of errors (Barrett, 2009). For example, even if the proper domain of the mechanism was conspecifics alone, the mechanism might still be broad enough to capture all animate motion, if the costs to false positives were not particularly high. Or the mechanism could be quite specific, if there were benefits to having a narrower target of detection, e.g., humans only. In either case, the answer will depend on the details of the actual cues or cue combinations that the mechanism has been selected to use. In the case of infants' sensitivity to biological motion we don't yet know the complete answer about how narrowly it distinguishes its inputs, though we have some hints from studies that examine the specificity of infants' reaction to different kinds of motion stimuli.

One possibility is that infants are sensitive to a basic anatomical structure that all vertebrates share, namely a hierarchical nesting of limbs that move in a pendular fashion. This hypothesis initially received encouragement from computational analyses, which revealed that algorithms using *local rigidity*—i.e., an invariant distance between joints as they rotate around each other—were successful at recovering the appropriate connectivity patterns of biological form under a wide range of conditions (Hoffman & Flinchbaugh, 1982; Webb & Aggarwal, 1982). However, subsequent experimental work has provided only mixed support for the idea that local rigidity captures the infants' attention in biological motion (e.g., Bertenthal, Proffitt, and Kramer, 1987; Bertenthal, 1993).

Another property of biological motion that infants might detect is *common motion*—i.e., infants may identify elements that move together and perceive them as a single unitary form. Bertenthal et al. (1987) found that infants discriminate a regular point-light walker from a point-light walker in which the temporal phase relations are perturbed. Interestingly, infants seemed to notice such perturbations at 3-months, but not anymore at 5-months. This result stands out in the biological motion literature, because several other studies have found highly similar performance across age groups (for a review, see Bertenthal, 1993). It is possible that *some* of the properties of biological motion that infants attend to change over time, while others remain constant.

So far, evidence suggested that infants become sensitive to biological motion around 3-months of age. This finding is consistent with the idea that either visual experience and/or postnatal maturation of visual structures play an important role in the development of biological motion perception. Recently, however, Simion et al. (2008) found that infants as young as 2-days-old discriminated an upright point-light display of a

walking hen from a scrambled point-light display, suggesting that even neonates, with hardly any visual experience, may be sensitive to biological motion. In a second experiment, 2-day-old infants also attended more to a point-light display of a walking hen than to a scrambled display. Thirdly, neonates attended more to an upright walking hen than an inverted hen (*inversion effect*). These results together suggest that infants may come into the world sensitive to the configural properties of biological motion, and that the constraints they use to identify animates are orientation-specific. Finally, that the babies responded to the biological motion of a hen suggests that the perceptual mechanism involved may not be tailored to any particular species. There are several scenarios, not necessarily mutually exclusive, that are consistent with this. For example, given that sensitivity to biological motion is present in other species (e.g., Blake, 1993; Dittrich, Lea, Barrett, & Gurr, 1998; Parron, Deruelle, & Fagot, 2007; Mascalzoni, Regolin, & Vallortigara, 2010), the mechanism may be phylogenetically old with a conserved design. It could also be that the selection maintaining it comes primarily from the benefits of detecting conspecifics, but there has not been strong selection to eliminate false positives from other species. Or, it could be that detecting walking animates of any kind provided sufficient benefits to infants (e.g., in detecting danger) that selection favored an early developing mechanism sensitive to motion of many species. To discriminate these hypotheses, finer-grained studies of infants' sensitivities would be needed.

Summary. Developmental research suggests that infants, from a very young age, are sensitive to biological motion, and preferentially attend to biological motion over other, controlled stimuli. Infants' sensitivity to biological motion is orientation-

specific—infants do not discriminate, nor do they preferentially attend to, biological motion that is inverted 180° (*inversion effect*). Although more work is needed to pinpoint the properties of biological motion that capture infants' attention, it appears that infants are sensitive to the relative motions of body parts, as is the case with local rigidity and common motion. Infants' ability to recognize the human body morphology seems to be later developing, towards the end of the first year. Finally, some evidence suggests that the constraints that infants' bring to bear in perceiving biological motion are not specific to the species being perceived (Simion et al., 2008). If this result is robust, we may speculate that the systems that infants use to perceive biological motion are evolutionarily old and shared with other primates (and other vertebrates), and / or that their function is not primarily to detect conspecifics.

Section 3: Inferring Goals and Other Mental States from Motion Dynamics

“The movements of lines and figures are the stimuli; but these movements become anchored in a field of objects and persons and are interpreted as acts.”

—Fritz Heider and Marianne Simmel, 1944

Both animate and inanimate objects move, and both kinds of motions are caused: a billiard ball colliding with another causes it to move across the table, and a lion appearing from behind a tree causes a zebra to run. But the kinds of causation that drive the behavior of inanimate and animate objects are not the same. Animate agents have sensory and decision-making systems that guide their behavior in the service of goals,

and inanimates do not. This is reflected in different patterns of spatiotemporal contingency in the perceptual array: billiard balls move only after direct contact, for example, whereas zebras can react at a distance. While spatiotemporal contingency is important in the inference of all kinds of causation, the patterns of contingency underlying goal-directed behavior can have unique features, such as coordinated or related actions between two agents at a distance (the lion moves towards the zebra and the zebra moves away in response). From early in infancy human minds become sensitive to the signatures of goal-directedness in animate motion, and a growing body of work is shedding light on the kinds of contingencies to which infants are sensitive.

In the previous section, we focused on the properties of biological motion that infants attend to. As we have seen, developmental researchers have examined the specific properties of biological motion that infants use to navigate their visual attention to social agents (Fox & McDaniel, 1982; Bertenthal, 1993; Simion et al., 2008). However, some of the properties that infants use to cue into the social domain are not properties of individual agents, but instead are dynamical properties that emerge when two (or more) agents interact. Such properties are sometimes called ‘socially contingent’ or ‘relational’ because they transcend individual agents (Fiske, 1991; Thomsen, Frankenhuys, & Carey, in preparation).

Social contingency. Rochat, Morgan, and Carpenter (1997) investigated whether 3-month-old infants are sensitive to social contingency, in which the behavior of one agent is (partly) predictable from the behavior of another agent. The infants watched two displays side-by-side, each depicting two discs (blue and red) moving across the screen. The motion of the red disc was identical on the left and right display, and similarly for the

blue disc. The only difference was that in one display the discs were moving relationally—as if they were ‘chasing’ each other—while in the other they were moving independently. The results showed that 3-month-old infants looked longer at the relational (or chasing) motion.

There are two different kinds of contingent motion that could have generated the preferential looking in the study by Rochat et al. (1997). Chasing motion, in the sense of pursuit and evasion, has (at least) two characteristic features: first, the chaser takes the shortest path to its victim (‘attraction’), and second, when the chaser comes close, the victim accelerates away (‘fleeing’). Both attraction and fleeing allow for the prediction of one agent’s behavior based on the motions of the other agent. Were the infants attending to the attraction or the fleeing component of the displays, or to both, or even to their interaction? This issue remains unresolved, but we are currently running studies that try to address it. In these studies, we show infants attraction without fleeing and measure their visual behavior (Frankenhuys, Johnson, House, & Barrett, in preparation). To an adult observer, such attraction without fleeing may look like ‘playing’. Whether young infants also interpret dynamic motion displays in such goal-directed terms is an important question, to which we now turn.

Categorizing motion. We have so far focused on the perceptual features of the social world that infants attend to. This work by itself, however, is not tailored to address whether infants interpret such stimuli as *goal-directed*, nor *which* goals they attribute to the objects. Given appropriate spatial and temporal parameters, adults are inclined to interpret dynamic motion displays in goal-directed terms (Heider & Simmel, 1944), even with a single geometrical shape (Scholl & Tremoulet, 2000; Tremoulet & Feldman,

2000). Recently, a cross-cultural study found that adults in two different cultures attribute the same goals to the same patterns of motion of interacting shapes on a computer screen, suggesting cross-cultural similarity in the underlying processes of inferring goals from motion (Barrett, Todd, Miller, & Blythe, 2005). While participants from the two cultures, German college students from Berlin and Shuar horticulturalists from Amazonian Ecuador, had very different cultural backgrounds and life experiences, they sorted films of moving dots into categories of fighting, chasing, playing, and following in almost identical fashion, and Shuar children made similar categorizations by age 4. This suggests that goal-directed motion is not merely perceived differently from inanimate motion, but that specific goals are inferred from the motion trajectories, and that there is substantial cross-cultural universality in the development of the underlying inferential mechanisms.

Developmental tasks. How do infants interpret social stimuli? Inferring the goals of agents based on their motions, and predicting their behavior using these goals, are different adaptive problems. Infants do not speak, and thus many of the methodological tools that are used with adults are not suitable (Proffitt & Bertenthal, 1990). Developmental research relies primarily on measures of visual behavior, sucking rates on a pacifier, changes in heart rate, and more recently also brain activity. Most research to this date, however, is based on looking times (for more discussion of looking time methods, see Haith, 1998; Munakata, 2000; Sirois & Mareschal, 2002; Aslin, 2007).

Preferential looking. The work on social contingency by Rochat et al. (1997) used a preferential looking paradigm, in which visual behavior is measured in response to simultaneously presented displays. This method allows researchers to get a good handle

on: 1) whether infants discriminate between displays, and 2) whether infants have a preference for one display over the other. However, it is usually not possible to infer from visual discrimination alone whether an infant notices a perceptual difference or imbues the displays with different conceptual interpretations (Sirois & Jackson, 2009). For this reason, developmental researchers interested in exploring infants' *understanding* of goal-directed motion tend to rely on methods other than the preferential looking paradigm. One method commonly used to study conceptual understanding in infancy is the habituation paradigm (see Section 2, *Habituation*); what is novel tells us something about what is familiar, and in some cases what is familiar may depend on the *interpretation* of previous events.

Inferring goals from motion. Rochat, Striano, and Morgan (2004) used the habituation method to investigate whether infants perceive certain kinds of social contingency as goal-directed. Four- and 9-month-old infants repeatedly watched a display depicting one disc chasing another (e.g., red chasing blue), until looking times decreased. Rochat et al. reasoned that if the infants were bored primarily by the perceptual features of the chasing event, then they would be expected to stay bored if a role reversal occurred (with blue chasing red), because this would be perceptually very similar to what they had seen before. However, if the infants interpreted the agents' motion as goal-directed, and had assigned a different goal to the chaser (catching the fleeing agent) and to the fleeing agent (escaping the chaser), then they should longer at a role reversal, because when a role reversal occurs the agents have novel goals—exactly opposite to what they were before. The results indicated that infants in the younger age group (4-month-old) did not regain interest when shown the role reversal. However,

infants in the older age group (9-month-old) *did* increase their looking time, suggesting that they had assigned different goals to the chaser and the victim.

A leaner interpretation would be that the older infants had merely *associated* a particular color with a particular motion dynamic—for example, the red disc moves at a constant velocity, while the blue disc sometimes bursts into acceleration. If this was the case, the infants could have dishabituated without having inferred anything about goals. To control for this possibility, Rochat et al. (2004) tested a new group of 9-month-old infants. These infants watched two discs (red and blue) move *independently* across the screen, until looking times decreased. Next, the colors were flipped in the test trials. This time the older infants did not dishabituate to an inversion of color, suggesting that the dishabituation in the chasing condition had specifically occurred because the infants had noticed a reversal of goals.

Violation-of-expectation. Another method for exploring infants' conceptual understandings is the violation-of-expectation paradigm (Baillargeon, Spelke, & Wasserman, 1985; Woodward, 1998). The violation-of-expectation method assumes that infants will look longer at events that violate their expectations, i.e., surprising events. For instance, an infant may first watch the beginning of an event (e.g., a ball rolling towards the edge of a table), and is subsequently presented with two event outcomes—one of which is “expected” (e.g., the ball rolls over the edge and falls on the ground) and one “unexpected” (e.g., the ball rolls over the edge and keeps hanging in the air). The method supposes that *if* an infant has expectations about gravity, then it will look longer at the unexpected (or surprising) outcome (Baillargeon, Wu, Yuan, Li, & Luo, 2009).

Predicting behavior from goals. One advantage to interpreting the behavior of animate agents as being driven by unseen goals is that it can allow better prediction of behavior than just extrapolating observed motion trajectories. In a clever demonstration of this, Gergely et al. (1995) used the violation-of-expectation method to show that 12-month-old infants (and later, 9-month-olds; Csibra, Gergely, Biro, Koós, & Brockbank, 1999) can use inferred goals to predict unseen events in the future which are, crucially, different than what they have seen the agent do before but consistent with the agent's goals. During a familiarization phase, 12-month-old infants watched a small ball jumping over a barrier to reach another, larger ball. In the test phase, they moved the barrier so that it was no longer between the two balls. Would the small ball then approach the large one the same way it had before, by jumping—or would it move in a straight line?

Gergely et al. (1995) argued that the straight-line trajectory could be seen as most consistent with the ball's “goal” of reaching the other ball, because the jumping behavior was only a means to an end, mandated by the presence of the wall. On the other hand, the jumping was closest, perceptually, to what the infant had been habituated to, and indeed, the infant had never seen the straight-line behavior. As predicted, the infants looked longer at the jumping than at the straight trajectory when the wall had been moved, consistent with the hypothesis that infants attributed a goal to the ball and predicted that it would perform the most efficient behavior to achieve it. This work has since been replicated for different goals, such as pursuit (Csibra, Biro, Koós, & Gergely, 2003) and also by different labs (Wagner & Carey, 2005). At least by one year of age, therefore, infants can use not only motion to infer goals, but they can then use these

attributed goals to predict future motion.

More mental states in motion. As psychologists are well aware, the motion of animate agents is caused by more than goals alone. Animals have perceptual systems with which they gather information about the world, form internal representations based on that information (which we sometimes call “knowledge” or “beliefs” depending on circumstances), and develop attitudes, emotions, and motivations with respect to those representations (e.g., “I saw ice cream in the fridge yesterday, and I want to eat it now”). In turn, all of these internal states, in combination with goals, influence externally observable motion (e.g., to avoid hunger, move to fridge, open door). Many of these internal mental states, while they are themselves hidden, can both be inferred from motion (e.g., if an agent comes upon a snake on the path and leaps back, then the agent has probably seen the snake) and can be used to predict it (e.g., the agent’s future path will probably be away from the snake). As it turns out, human minds, beginning in infancy, are sensitive to the relationship between external behavior and internal states (for reviews, see Carey, 2009; Baillargeon, Scott, & Ze, 2010). Several recent studies, for example, have shown that infants calculate what an agent knows or believes based on its location in space and time with respect to other objects, and use this to predict future motion trajectories (Onishi & Baillargeon, 2005; Surian, Caldi, & Sperber, 2007; Southgate, Senju, & Csibra, 2007; Southgate, Chevallier, & Csibra, 2010).

For example, Surian et al. (2007) showed that 13-month-old infants use the spatiotemporal array of a scene to compute what an agent can and can’t see, and then use this to predict the agent’s future behavior. In this case, they showed an animated caterpillar watching food items, cheese and an apple, being hidden behind two different

screens. The caterpillar would then move towards one of the screens and take a bite of the food item behind it, thereby demonstrating a preference for one of the food items. In the test trials, Surian et al. showed that the 13-month-olds were surprised when the caterpillar approached a food object that it dispreferred when it could see the item, but they were not surprised when it approached the item when the items had been switched behind the screens when the caterpillar could not see. This implies a combination of visual perspective-taking on the part of the caterpillar and representations both of the caterpillar’s goal state (i.e., which food it wanted to eat) and its belief state (i.e., where it had last seen the food). Studies by Onishi & Baillargeon (2005) and Southgate et al. (2007) have shown similar knowledge tracking abilities early in childhood. These studies show that interpreting and predicting the motion trajectories of animate agents is not simply a matter of extrapolating from previously observed trajectories, but rather, using motion to form representations of internal states such as goals, preferences, and beliefs, and using these representations to predict future movement.

Summary. Using motion dynamics to infer goals and other mental states is not something that all species do, or do to the same degree as humans. While many other species may be sensitive to motion in the same ways that humans are, they may not be capable of interpreting it in the same way. Beginning at an early age, humans parse the structure of action, and make inferences about the relationships of particular elements of the action to an intended outcome. In the study by Csibra et al. (1999), for example, 9-month-old infants interpret jumping over a wall as a means to an end, i.e., reaching a fellow ball, and adjust their expectations about behavior when the situation changes so as to make this action unnecessary to reach the goal. The ability to engage in such forms of

causal reasoning has probably given humans substantial evolutionary benefits. For example, the ability to interpret others' behavior in a goal-directed way, rather than a series of arbitrary movements, may give human children a substantial benefit in social learning and imitation (Want & Harris, 2002). While we do not yet know the exact details of the developmental mechanisms that allow children to begin to reason about goals and other mental states in infancy, research is beginning to reveal how infants extract social meaning from the array of spatiotemporal contingencies around them.

Section 4: Discussion

Just as “biological motion” refers to an enormous and complex category of things in the world, so is the set of perceptual and inferential challenges facing an infant trying to comprehend it. Here we have presented a brief sketch of how infants solve three of these challenges: perceiving motion in the first place, discriminating the motion of animate things from inanimate ones, and making use of the information in animate motion to interpret what the actor is trying to do. This research shows that by the second year of life, the human child is already a sophisticated social perceiver. And the child's skills in motion perceptions are not exhausted by those we have reviewed here. For example, while we have focused on whole-body and postural motion, such as motion that can be detected in point-light displays or moving dots, babies are also sensitive to the changing patterns of expression on peoples' faces and the subtle movements of body parts that are a critically important part of human social interaction. As we have stressed, virtually from the moment infants are able to perceive biological motion, they begin to

make use of it.

An important question—in addition to continuing to document the development of children's skills in this domain, many of which undoubtedly remain to be discovered—is the question of mechanisms, both developmental and cognitive. What are the mechanisms that enable even very young children to, for example, discriminate between point-light displays of upright versus inverted walking chickens, or to be surprised when a dot on a computer screen takes one path rather than another? Here as elsewhere in cognition there are both proximate and ultimate questions (Tinbergen, 1951, 1963). Proximally, what are the minimum computational abilities or mechanisms that we need to attribute to an infant to account for their behavior in biological motion tasks? What causes the developmental changes that lead to the emergence of those abilities? And ultimately, did the mechanisms that an infant brings to bear in solving a given problem evolve specifically *in order to* solve that problem, or for something else? For many of the results we have reviewed, these remain open questions.

For example, one could argue that when we look at biological motion, our perceptual and conceptual systems are performing a kind of causal analysis, if only implicitly. When we observe a person walking, for example, we perceive, or infer, that it is the contact of their feet with the ground, followed by the pulling of each leg backwards, that pushes the walker forward. When we observe a zebra being startled by a lion we perceive, or infer, that the zebra *saw* the lion and was frightened by it. Are these inferences the result of a single cause-and-effect interpretation system, one that works across all instances of change over time, extracting the regularities through learning? Or are there systems specific to biological motion per se? Or, even more specific, are there

systems specific to postural versus whole-body motion, or to motion that can be explained via goals alone versus motion that requires the attribution of belief states? In order to answer these questions, we need to develop more specific hypotheses about what the alternative designs would be, why they might exist, and what would be the relevant tradeoffs, costs, benefits, and predicted patterns of performance that we would see from different kinds of systems (Cosmides & Tooby, 1994; see also Frankenhuys & Ploeger, 2007). Surprisingly, while the developmental literature contains myriad examples of what infants can do, we know much less about the evolutionary and developmental histories of the underlying mechanisms.

We are encouraged, however, by the growth of research in this area, and about what it stands to tell us not just about the developmental of biological motion perception per se, but about processes of cognitive development in general. Biological motion perception is a paradigm case of babies developing a skill that allows them to navigate in the world, and as such, it offers a microcosm of all the interesting questions in cognitive development, ranging from questions about what is “built in” to the system that allows it to do what it does, to questions about how developing brain systems self-organize on the basis of the experiences available to the infant. We look forward to the new discoveries that are waiting to be made about what babies can do.

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