Annu. Rev. Psychol. 1996. 47:431–59

ORIGINS AND EARLY DEVELOPMENT OF PERCEPTION, ACTION, AND REPRESENTATION

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KEY WORDS: perceptual development, motor development, conceptual development, cognitive development, sensorimotor development, perception-action, representation

ABSTRACT

Research relevant to the origins and early development of two functionally dissociable perceptual systems is summarized. One system is concerned with the perceptual control and guidance of actions, the other with the perception and recognition of objects and events. Perceptually controlled actions function in real time and are modularly organized. Infants perceive where they are and what they are doing. By contrast, research on object recognition suggests that even young infants represent some of the defining features and physical constraints that specify the identity and continuity of objects. Different factors contribute to developmental changes within the two systems; it is difficult to generalize from one response system to another; and neither perception, action, nor representation qualifies as ontogenetically privileged. All three processes develop from birth as a function of intrinsic processing constraints and experience.

CONTENTS

0066-4308/96/0201-0431$08.00

INTRODUCTION

Recent findings on the perceptual, motor, and conceptual competencies of young infants challenge long-held beliefs about early development. According to most classical developmental theories (Baldwin 1906, Bruner 1973, Piaget 1952), newborns are endowed with only a very simple repertoire of sensorimotor behaviors that are gradually integrated and internalized. The capacity for representation and conceptualization is presumed to emerge from this developmental process. It is not clear, however, that this position is still tenable. Indeed, the capacity for representation may be available at birth or soon thereafter (Carey & Gelman 1991; Eimas 1994; Leslie 1988; Karmiloff-Smith 1992; Mandler 1988, 1992; Mounoud 1993; Spelke 1994).

This new view requires a reconceptualization of the developmental relations among perception, action, and representation. Most models of perceptual processing now suggest that different sensory inputs converge into a unified representation that precedes both thought and action (Marr 1982, Ungerleider & Mishkin 1982). This monolithic view of perception suggests that assessing what is perceived is independent of whether the response measure is based on an action or a perceptual judgment. From a developmental perspective, this view implies that evidence for representation of objects should be manifested by thought and action at the same age. It is now apparent, however, that this view is obsolete. The paradigmatic case for this assertion is the conflicting and contradictory evidence on object permanence. Most infants do not reach for an object hidden by an occluder until they are 8–9 months old (Butterworth 1982). This failure to recover the hidden object is interpreted as evidence that infants do not think about objects that are not perceptually present (Piaget 1954). Nevertheless, infants as young as 3 months old show evidence that they represent the continuity and solidity of objects—at least when the test of object permanence demands nothing more than a visual fixation by the infant (Baillargeon 1987, Diamond 1991, Spelke et al 1992). In order to eliminate these confusions and contradictions in the literature we must adopt a new framework for understanding the early perceptual, motor, and cognitive development of infants.

An intriguing possibility is suggested by Goodale & Milner (1992), who propose that the visual system is divided into two functionally dissociable pathways. One is concerned primarily with the perceptual control and guidance of actions, the other primarily with the perception and recognition of objects and events. This dichotomy resembles the one advanced previously by

Ungerleider & Mishkin (1982) that the visual brain consists of two systems, a "what" and a "where" system. It is nevertheless different, because the emphasis is not on the input side of visual processing but the output side or the responses elicited by the visual information. "What" vs "how," not "what" vs "where," best captures this functional dissociation.

This functional dissociation between control and recognition represents the departure point for the current review. Although virtually all the evidence for this dissociation is based on neurophysiological findings with monkeys and neuropsychological findings with human adults, it is plausible that this dissociation is present early in development, given that the proposed division of labor maps onto different neural pathways that are all developing within the first year (Johnson 1990). One may speculate that this functional dissociation is not limited to visual processing, but extends to other modalities as well.

A brief review of the processing differences between these two perceptual systems will clarify further why behaviors mediated by the perceptual control system are functionally dissociable from behaviors mediated by the object recognition system.

1. Object recognition includes processes that make contact with information perceived at some prior time and stored in some representational form. Successful recognition depends on both how the visual scene is parsed and on the representational format of the stored information. By contrast, the perception and control of actions is directed toward present information and, if anything, includes a prospective view toward information in order to offset delays produced by neural transmission and the inertia of body segments.

2. The second difference is related to the first and involves the coordinate system for perceiving objects. Perception of objects involves an allocentric or world-based coordinate system such that displacements are seen relative to a stable or constant world. By contrast, acting on an object requires that the object be referenced egocentrically—i.e. relative to the effector system involved in the action (Paillard 1991).

3. A third difference concerns the coding and preservation of modality-specific information. Objects are typically specified by multimodal sources of input, but the information is stored in a modality-specific format. This provision is necessary to explain how observers recognize specific features of objects, such as its color or pitch, as well as the covariation between features specified both within and between modalities. By contrast, perceptual information is represented by the action system in an amodal format comprised of body-scaled information. This format transforms all sensory inputs into the appropriate muscle synergies necessary for producing coordinated actions in response to local conditions. It is thus not essential to represent the modality of the sensory input, because the function of this information is the same regardless of its source.

4. The last processing difference concerns the role of awareness in the perception of information. Objects that are not consciously processed are neither recognized nor stored for future recall. Recognition requires that observers direct their attention toward selected objects and know when they are perceiving the relevant information. Conversely, information necessary for detecting self-motion and controlling other actions operates without any necessary awareness by the observer. For example, patients with brain lesions who are unable to recognize objects are nevertheless able to reach for these objects and to anticipate their size and shape correctly while reaching (Goodale et al 1991, Weiskrantz et al 1974).

In the remainder of this chapter, I summarize recent research relevant to the development of these two perceptual systems, noting that different factors contribute to developmental changes within the two systems, that it is difficult to generalize from one response system to another, and that neither perception, action, nor representation qualifies as ontogenetically privileged. All three processes develop from birth as a function of intrinsic processing constraints and experience.

PERCEPTUAL CONTROL OF ACTIONS

All spatially coordinated behaviors, such as visual tracking, reaching, and sitting, require that perceptual information and action are coupled. In the words of James Gibson (1979), “We must perceive in order to move, but we must also move in order to perceive” (p. 223). Perceptual information relevant to the regulation of movements includes spatio-temporal patterns of optic flow at a moving eye, haptic patterns of joint, muscle, and skin deformations, and so on. All of this information changes in ways that are lawfully related to the properties of the environment and the action itself. For example, reaching for an object is guided by perceptual information that changes as the reach is executed. These perceptual changes modulate the effectors to insure that the reach is successful (Jeannerod 1994). Similarly, perceptual information is necessary to maintain postural equilibrium, but again the information changes as the posture is adjusted in response to that information (Howard 1986). From this perspective it is arbitrary and misleading to conceptualize perception and action as independent processes. It is more parsimonious to view these two processes as opposite poles of a functional unit or action system, along the lines suggested by Reed (1982, 1989).

Newborn Actions Are Spatially Coordinated

When are perception and action first coupled? Until recently, the answer to this question was dominated by Piaget’s (1952) view of sensorimotor development. He asserted that perceptions and actions are initially independent processes that are coordinated gradually with experience. The implication of this proposal is that the early behavior of the neonate is essentially random and insensitive to contextual information. Recent research suggests that some rethinking of this extreme position is necessary.

During the past decade, researchers have observed that newborn infants are capable of performing many actions that are regulated by perceptual information. For example, newborn infants orient to sound (Clifton et al 1981, Muir & Field 1979, Zelazo et al 1984), scan differently in different stimulus conditions (Haith 1980), visually track moving targets (Bloch & Carchon 1992, Kremenitzer et al 1979), increase the frequency of hand-to-mouth contacts following oral delivery of a sucrose solution (Blass et al 1989, Rochat et al 1988), and show hand extensions toward a visible moving object (Trevarthen 1984, von Hofsten 1982). Of course, these behaviors are fragile and inconsistent, which explains why they were overlooked for quite some time. Subtle changes in posture or stimulus parameters are often sufficient to disrupt these coordinated behaviors. For example, Roucoux et al (1983) have shown that neonates sometimes experience difficulty in tracking objects visually because of the instability of their trunks, which do not yet move independently of their heads.

It thus appears that newborns enter the world prepared to perceptually regulate actions that are essential to the survival and adaptation of the neonate. An intriguing suggestion is that behaviors practiced in the womb show an advantage at birth (von Hofsten 1993). For example, proprioceptive guidance of the hand to the mouth is readily observed in neonates (Butterworth & Hopkins 1988, Rochat et al 1988). Furthermore, Butterworth & Hopkins (1988) report that the mouth is more likely to remain open during arm movements when the hand goes directly to the mouth rather than first touching other portions of the face. Soon after birth, this response is observed more frequently prior to feeding than following feeding (Lew & Butterworth 1995). Taken together, these findings suggest significant specificity in the coordination of hand and mouth at birth.

The evidence for the coupling of perception and actions at birth should not be misconstrued as suggesting that these systems are fully developed or that new couplings will not emerge. Contemporary theorists emphasize that development involves a confluence of factors that include neural and biomechanical changes as well as environmental and task factors (Newell 1986, Savelsbergh & van der Kamp 1993, Thelen 1995). Practice and experience with a specific action system contribute to its development. Some of the best examples involve behaviors traditionally viewed as motor skills, such as posture and gait (Sveistrup & Woollacott 1995, Thelen & Ulrich 1991).

One reason that practice and experience are not sufficient to capture the process of developmental change is that the infant is also changing in body proportions and neural connectivity. For example, Banks (1988) reports that the optical components of the eye are still growing at birth, the photoreceptors will mature and migrate during the first few months, and the dendritic arborization of the central visual pathways will continue to develop for some time. These changes inform us that the resolution and projective structure of the visual image will improve with development. Likewise, the perception of spatial layout and of the relative depths and distances of objects will improve with development (Yonas & Owsley 1987).

It is perhaps even more important to point out that oculomotor functioning will show significant improvement during early development. Saccadic localization of stationary and moving targets involves a direct mapping between retinal location and neuromuscular stimulation of the relevant eye muscles. Initially, this localization process is imprecise and involves multiple saccades before the target is foveated (Aslin & Salapatek 1975). No doubt some experience is necessary to learn the precise relation between the neural pulse duration and saccade magnitude necessary for rotating the eye to the correct position. It is still somewhat surprising that the calibration process requires over four months to complete, especially when estimates suggest that infants make between 3 million and 6 million eye movements by 3.5 months of age (Haith et al 1988). One especially intriguing hypothesis about this lengthy process is that the mapping of retinal locus onto an oculomotor command is constrained by the changing distribution of photoreceptors in the retina (Aslin 1988). It is thus necessary for the infant to adapt continually to this changing sensorimotor relation during early development.

This last example illustrates especially well that actions are spatially coordinated from birth but become better tuned or coordinated as a function of neural development and experience. Although the process by which perceptuomotor behaviors develop is rarely investigated, researchers have begun to recognize that motor skills are not only products of this developmental process, but are intimately involved in the process itself.

Reciprocity Between Action and Perception

Perceptual control of behavior depends on the detection of the relevant perceptual information as well as the functionality of the actions available to infants. As simple actions such as visual tracking or sucking are practiced and repeated, they become better coordinated and controlled, and perceptual information is detected with increasing specificity. An excellent example of these changes is revealed by research on the minimum audible angle necessary for detection of the direction of a sound source. In this task infants are expected to turn their heads to the right or left of midline if they are capable of localizing the sound (Ashmead et al 1987, Morrongiello 1988). Ashmead et al (1991) summarize the data from a number of studies to show that the minimum detectable difference decreases rapidly between 8 and 24 weeks of age and then continues to decrease more gradually through 80 weeks of age. It is noteworthy that the most rapid improvement occurs during and just following the time that infants are developing independent control of their heads (Bayley 1969).

The preceding example is an excellent illustration of the reciprocity that exists between action and perception in development. As new actions become available, new opportunities for exploring the fit between the self and the environment emerge (Adolph et al 1993a). Another example of this proposal is associated with the development of crawling or self-produced locomotion. Perceptual guidance is necesary to assure movement without collisions on a safe and sturdy surface of support (Gibson & Schmuckler 1989).

Bertenthal & Campos (1990) report that perceptual sensitivity to objects and surfaces changes significantly following some experience with crawling. For example, Campos et al (1992) report a series of studies showing that precrawling infants show no evidence of fear (as indexed by heart rate acceleration) when lowered onto the deep side of a visual cliff (simulating an apparent drop-off in height), whereas crawling infants show a significant degree of fear. Fear is also shown by precrawling infants if they are given sufficient experience with self-locomotion in baby-walkers. Apparently, such experience with perceptual guidance of self-locomotion changes infants' perceptual appreciation of an apparent cliff. Precrawling infants do not show fear of heights not because they cannot perceive depth (Yonas & Owsley 1987) but because they do not yet need to coordinate the perception of surfaces with their direction of heading.

Similar findings are reported by Gibson et al (1987), who tested crawling and newly walking infants on their mode of locomotion on two surfaces varying in rigidity (plywood vs waterbed). Infants capable of upright locomotion differentially explored the two surfaces and chose to walk only on the rigid surface. Crawling infants did not show different behavior on the two surfaces. In more recent research, Adolph et al (1993b) report that newly walking infants, but not crawling infants, differentiate between inclined and declined surfaces by choosing a more stable posture, such as sitting or crawling backwards, when traversing the down-sloping surface.

Another compelling example of the reciprocity between perception and the development of new actions is offered by Bushnell & Boudreau (1993). Adults detect many different properties of objects, such as size, texture, weight, hardness, and temperature, from haptic explorations (Lederman & Klatzky 1987). Some of these properties, such as size and temperature, demand minimal control of the hand and fingers, whereas other properties, such as weight and shape, require much greater control. Bushnell & Boudreau reviewed the ages at which infants first discriminate different object properties and concluded that the sequence corresponds to developmental changes in the control of the hand and fingers. For example, infants detect size within the first few months, but texture, temperature, and hardness are not detected until around 6 months of age, and weight and shape are not detected until even later. Although the evidence for this claim is still incomplete, alternative interpetations (e.g. that these observations result from differential exposure to different object properties) are unlikely, given the ecology of the infant's environment.

New perceptions and new actions are related through a dynamic process involving the selection of new behaviors in response to new sources of variability in the organism and in the environment (Bertenthal et al 1994, Manoel & Connolly 1995; Thelen 1989, 1995). Consider the coordination of the limbs during forward prone progression. Most infants crawl with their abdomens on the ground before crawling on hands-and-knees. Once they develop sufficient strength to support themselves on hands-and-knees they briefly show many different patterns of interlimb coordination before converging on a pattern of moving diagonally opposite limbs simultaneously (Freedland & Bertenthal 1994). The selection of this specific pattern is a function of perceiving the optimal coordinative structure to insure balance while minimizing the expenditure of energy.

Another example related to the development of crawling experience involves the spatial coding of a hidden object. Numerous studies report that crawling infants show improved localization of objects following a displacement of the infant or the object (Bremner & Bryant 1985, Horobin & Acredolo 1986). Precrawling infants tend to code the location of an object with a body-centered frame of reference, presumably because this coding is initially necessary for successful orientation to the object. With the emergence of crawling, infants show a transitional period during which their responses vary. Eventually, they learn to update their initial spatial coding in response to the perceived displacement (Bai & Bertenthal 1992).

Thelen and colleagues offer additional examples of how the development of new actions, such as infant stepping, emerge following periods of increased variability (Thelen & Ulrich 1991, Ulrich et al 1991). Overall, this research suggests that perceptuomotor development is an emergent process in which a goal-directed organism seeks stable outcomes to specific tasks.

Perception Is Prospective

Our actions, like those of all animals, are coupled to the spatial layout and demand perceptual guidance and control (Lee 1993). In locomotion, for example, we must make contact with some surfaces while avoiding others. In general, it is necessary to control actions prospectively and not retrospectively (i.e. following feedback from the action) in order to insure smooth and safe movement (von Hofsten 1993). The inertia of the limbs and the time lags of neural conduction demand some anticipation of future actions (Haith 1994, von Hofsten 1993). Information needed for the specification of upcoming events is available in the optic and acoustic arrays and is used for controlling future actions. As adults, we readily appreciate the temporal component in the control of actions. For example, we know that it is necessary to be in the right place at the right time to catch a ball, meet a person, or give a lecture. Recent findings in the literature reveal some remarkable examples of future-oriented behavior by infants.

One of the earliest examples of prospective behavior is seen in the development of smooth visual pursuit of moving targets. In order to track an object smoothly it is necessary to anticipate its future position: The programming of eye movements takes time. Shea & Aslin (1990) presented infants with 2° white squares that moved at a range of fixed velocities between 3 and 12 degrees per second. They reported that the pursuit system is clearly functional by 7 weeks of age and suggested that slower speeds and larger targets could be detected at younger ages. This suggestion is consistent with the findings of other investigators (Bloch & Carchon 1992, Kremenitzer et al 1979, Roucoux et al 1983), who report brief segments of smooth pursuit in newborns and one-month-old infants. The success of pursuit tracking at such young ages is especially impressive when it is recognized that eye movements may also have to compensate for unrelated head movements. In studies where the head was unrestrained during testing, young infants tracked a moving target with a combination of head and eye movements (Daniel & Lee 1990, Regal et al 1983, Roucoux et al 1983).

Another eye movement paradigm that shows early evidence of future-oriented behavior is the visual expectation paradigm pioneered by Haith (1993): Infants observe small pictures that alternate between the left and right of the center of the screen. After a few repetitions, 2- and 3-month-old infants begin to show anticipatory fixations to the location of the appearance of the next picture, even when the timing and location of the alternation patterns become more complex (Canfield & Haith 1991, Wentworth & Haith 1992). It thus appears that even very young infants can learn quickly how to control the location of their fixations in order to explore the changing pattern of information available in their visual world.

One of the most remarkable examples of prospective behavior by infants involves their reaching for moving objects. Von Hofsten (1983) studied infants' reaching for stationary and moving objects and reported that they began to contact objects in both conditions at the same age. By 18 weeks of age, infants could catch an object moving at 30 cm/s, and by 8 months infants could catch objects moving at 125 cm/s. In this study, a reach did not correspond to a simple reflex response. The objects were contacted at various locations along their trajectory, and the aiming and timing errors were quite small. These observations suggest that the infants were sucessfully controlling their reaches by extrapolating from the trajectories of the objects and modulating their motor responses. This modulation is a complex process involving the perception of both passive and active forces that vary from one reach to the next (Zernicke & Schneider 1993). In a related study, Robin et al (1995) observed 5- and 7.5-month-old infants reaching for a horizontally moving object. Infants usually reach with their ipsilateral hand for a stationary object (Perris & Clifton 1988). In this study, infants shifted to reaching with their contralateral hand when the object was moving, which increased the time available to intercept the target. Kinematic measures, such as velocity and duration of arm movements, converged with those reported by von Hofsten to suggest that infants aimed their reaches in anticipation of the future position of the moving object.

Prospective behaviors are also evidenced when infants learn to posturally compensate for a loss of balance (Bertenthal et al 1995, von Hofsten 1993), lean toward objects that are out of reach (McKenzie et al 1993, Rochat & Goubet 1995, Yonas & Hartman 1993), anticipate the size, shape, and orientation of objects that they are attempting to grasp (Lockman et al 1984, von Hofsten & Ronnqvist 1988), and guide their locomotion around obstacles (Gibson & Schmuckler 1989, Schmuckler & Gibson 1989). One interpretation of all of these findings is that infants become successful across tasks as they develop the capacity to represent future events. The problem with this cognitive interpretation is that it ignores developmental differences attributable to the coordination of different motor skills. A more parsimonious interpretation is that the prospective behavior displayed by infants is not contingent on a central representation but rather emerges piecemeal from the specific experiences that infants encounter through their actions. It is thus the dynamic interplay between actions and outcomes that fosters the development of prospective control. As infants experience new tasks that demand greater control, the precise timing of their actions will improve.

Perception Is Multimodal

In most situations, the perceptual information available for controlling actions is multimodal. Consider, for example, the control of posture during independent stance. Posture is specified by proprioceptive, vestibular, and visual flow information (Lishman & Lee 1973). It is a goal-directed behavior, even if it is not consciously controlled (Howard 1986). The individual's goal is to position the head and body relative to gravity and the surface of support. When a perturbation of this position is sensed, a postural compensation is initiated. One reason that this perceptuomotor response is so successful is that it is specified by multiple and redundant sensory inputs. This redundancy increases the likelihood of detection by even young infants who show rapid development of this perceptual-motor response.

Much of the research on the development of postural control tests infants in a "moving room." In this paradigm, the infant sits or stands on a stationary floor while the walls and ceiling move forward and backward. This movement produces visual information congruent with the head moving in the opposite direction. If the optical flow is perceived as specifying self-motion (as opposed to object motion), then the infant will show a postural compensation that varies with age and experience (Bertenthal & Rose 1995).

Lee & Aronson (1974) were the first to show that independently standing infants compensate posturally in a directionally appropriate manner in response to such visual flow information. Others subsequently demonstrated that optical flow information restricted to the peripheral portions of the visual field was sufficient to induce postural compensations (Bertenthal & Bai 1989, Stoffregen et al 1987). Additional evidence for the coupling between vision and posture was reported by Butterworth & Hicks (1977) and Bertenthal & Bai (1989), who showed that infants who could sit independently also responded with postural compensations of their trunk when tested in the moving room. It appears that an even earlier form of this coupling is present at birth. Jouen (1990) reported that newborn infants show postural compensations of their head when stimulated by an optical flow pattern of blinking lights located in the periphery of the visual field.

In the moving room paradigm postural compensations are induced by visual information, but it would be misleading to suggest that the response is controlled exclusively by visual inputs. Postural sway is specified visually by optical flow information, but it is also specified by more proximal stimulation from muscles, joints, and the inner ear. Studies involving mechanical perturbations of a platform reveal that somatosensory and vestibular systems also induce postural responses (Hirschfeld & Forrsberg 1994, Woollacott & Sveistrup 1994). Developmental changes in postural control involve learning to regulate the amount of force to compensate for the perceived displacement. Bertenthal et al (1995) studied infants during the period when they are learning to sit without support. They report that the compensatory forces necessary to maintain postural equilibrium become more precisely scaled to the perceived displacement of the trunk between 5 and 9 months of age. Performance improves not only because compensatory postural responses are more finely modulated, but also because the perceived displacements are detected more rapidly and precisely.

How do infants learn that different sources of sensory input are equivalent and converge on the same motor response? If sensory information is first represented in a modality-specific format, then it would appear necessary for infants to learn the relations between different sensory inputs, such as vision and touch. Indeed, this form of learning to coordinate different modalities is the bedrock of Piaget's (1954) theory of sensorimotor development. Yet current evidence suggests that this form of associative learning is unnecessary.

An alternative proposal is that all sensory inputs related to self-produced actions are represented in a common amodal format that maps directly onto an appropriate pattern of muscle activations (Lee 1993, Warren 1990). Such a common format is thought to insure that all sources of sensory information are transformed into the same body-scaled information necessary for modulating the motor response synergies involved in the performance of coordinated movements (Bertenthal & Rose 1995, Savelsbergh & van der Kamp 1993). For example, when an individual detects that support is perturbed, it is not important to determine which sensory input channel specified this loss of balance. The goal is simply to restore equilibrium, and this involves scaling the compensatory forces to the perceived displacement.

Another example of the equivalence of different sensory inputs for controlling actions involves the development of reaching. Historically, the prevailing view has been that reaching is initially visually guided (Bushnell 1985, Piaget 1952, White et al 1964), but more recent studies show that infants reach readily and accurately in the dark for sounding as well as luminous objects (Clifton et al 1991, Clifton et al 1994, Stack et al 1989). In one study (Clifton et al 1993), infants between 6 and 25 weeks of age were tested longitudinally to determine whether they required sight of their hands when beginning to reach for, contact, and grasp objects. Each session included trials of objects presented in the light and trials of glowing and sounding objects presented in complete darkness. The results revealed little variation as a function of experimental condition. Overall, infants first contacted the object in both conditions at comparable ages (light 12.3 weeks; dark 11.9 weeks), and they first grasped the object in the light at 16.0 weeks and in the dark at 14.7 weeks. Infants could not see their hands or arms in the dark; their early success in contacting the glowing and sounding objects indicates that proprioceptive information was sufficient to guide reaching. It thus appears that no single source of sensory information (e.g. visual, proprioceptive, or vestibular) is privileged in initially guiding actions.

Some of the most dramatic evidence for the amodal representation of sensory inputs is revealed by studies of neonatal imitation. Meltzoff & Moore (1983, 1989, 1994) and many others (see Anisfeld 1991 for a review) have shown convincingly that newborn infants imitate specific facial gestures (e.g. mouth opening) produced by an adult model. Such gestures cannot be visually guided because they involve movements that the infant cannot see—i.e. movement of the infant's own face. The correspondence between the perceived facial gesture and action by the newborn suggests that visual information concerning the adult's face is perceived amodally in a format that maps directly onto the appropriate muscle activation patterns (Meltzoff & Moore

1994). Currently, this claim remains fairly controversial because it necessitates the detection of a correspondence between the visual perception of the actions of a model and the proprioceptive perception of one's own actions. No complete explanation for this matching has yet been presented, although the spatiotemporal coding of the model's gestures may provide more specific information than assumed by most investigators (Bertenthal & Pinto 1993).

In sum, actions are most often guided by multimodal information. This redundancy may help to explain why the perception and control of adaptive behaviors, such as reaching, sitting, and walking, develop rapidly once the necessary muscle synergies are available. Moreover, the availability of multiple sources of information for modulating actions in response to local conditions increases the consistency, stability, and flexibility of any adaptive behavior.

Perception Is Context Specific

Recent theoretical and empirical advances in the study of motor control and coordination highlight that actions are a product of multiple factors including physical, physiological, and energetic components (Freedland & Bertenthal 1994, Goldfield 1993, Manoel & Connelly 1995, Thelen 1995, Turvey 1990). A principal implication of this view is that the same actions will not necessarily be observed in different contexts. For example, Grenier (1981) reported that reaching movements by newborns are much better coordinated when the head is stabilized than when it is unsupported. This finding is especially important because it emphasizes that context involves not only external factors, but also the ways in which different body segments are configured and interact. Zernicke & Schneider (1993) show explicitly that the forces responsible for moving limb segments are a function both of active forces (produced by muscle contractions) and of passive forces (corresponding to gravity and the inertial forces from the other moving body parts). Thus, it is apparent that there exist multiple constraints that determine whether or not an action will be performed in a specific context.

This contextual specificity is illustrated by the finding that newborn infants perform alternating step-like movements when held upright with their feet on a support surface. Within a few months, these movements disappear, presumably because they are inhibited by the development of higher-level cortical structures (Zelazo 1984). Curiously, however, similar movements are still observed in babies lying on their stomachs or backs (Thelen & Fisher 1982). These findings may be explained by a simple biomechanical calculation showing that more energy is needed to lift a leg to full flexion while upright than while supine. Although gravity is a constant force in the environment, it only becomes a constraint after the newborn period when infants begin experiencing rapid weight gains that decrease the ratio of muscle to subcutaneous fat in the legs. Experimental manipulations that changed the weight of the leg or the resistance of the leg to flexion (e.g. submerging infants in torso-deep water) showed that the presence or absence of stepping was systematically related to the biomechanical constraints of the situation (Thelen et al 1984, Thelen et al 1987). This simulation of developmental change highlights the important contribution of contextual variables.

The development of reaching in different postures is another example of the context specificity of motor control. Coordinated reaching is only possible in the context of a stable body posture (von Hofsten 1993, Paillard 1991). When infants incapable of sitting without support (22–26 weeks of age) are placed in a fully supported posture (e.g. supine or reclined), they tend to reach for objects with both hands (Rochat & Senders 1991, Rochat 1992). By contrast, infants capable of sitting without support (28–38 weeks of age) reach with one hand, regardless of their posture. The younger infants also reach with one hand when placed in a seated position, because they must compensate for a loss of balance by recruiting the other hand to help stabilize themselves in this position. Note that in this case infants shift to a different response because the task is different, not because they have undergone a change in neural or muscular control. The selection of a more stable response induced by behavior becoming more variable in a new situation or task appears to represent one of the few general processes in the development of new actions (Freedland & Bertenthal 1994, Manoel & Connolly 1995, Thelen 1995).

Additional evidence suggests that perception-action couplings are relatively specific and thus do not generalize to similar actions. For example, Rochat & Senders (1991) report a progression in hand-mouth coordination from bimanual action organized in mirror image symmetry toward an asymmetrical involvement of the hands. This same progression is repeated when infants begin to visually explore objects that are grasped, even though bimanual reaching is less flexible or functional. Likewise, visual control of a sitting posture does not generalize to visual control of a standing posture (Bertenthal & Bai 1989, Woollacott & Sveistrup 1994). It appears that infants must learn to modulate or control each new motor response de novo, even if the perceptual information (e.g. optical flow specifying self-motion) is readily processed.

There is an important moral to this section. It is misleading and contradictory to ascribe a specific perceptual skill to an infant based on one task. Performance is based on multiple factors; seemingly insignificant variables, such as postural stability or orientation, produce profound effects. Moreover, the presence or absence of the skill in question will also depend on the specific motor response necessary for performing the task. For this reason, researchers are well advised not to discuss these perceptual skills independent of the task or response assessed. A better approach is to determine whether the perceptual information is transformed into the appropriate motor response synergies, and to specify all the factors that contribute to this process. This strategy shifts the focus from assessing onset of perceptual skills to understanding how these skills develop.

OBJECT PERCEPTION AND RECOGNITION

The recognition system is distinguished from the perception-action system primarily by the fact that recognition is defined with reference to the past. If I recognize a student or a friend, for example, some immediately perceived information must match some previously stored information. Although theorists (Biederman 1987, Marr 1982, Rock 1984) offer little consensus on the representational format of this information, it is reasonably certain that the stored information is not an exact copy of the perceived scene. Logical and functional imperatives dictate that storing all the available information in the scene is neither necessary nor useful for specific tasks. The ordinary environment consists of a hierarchical nesting of information at multiple scales ranging from large objects, such as mountains and trees, to very small objects, such as leaves and cells; it is rich in structure and consists of places, surfaces, layouts, people, animals, etc. From any point of observation, a plenum of structured information is available, including the texture and composition of individual surfaces, the arrangement of those surfaces in the spatial layout, and the binding of some into distinct objects. What is perceived and recognized depends on the intentions and goals of the observer. The task of recognizing a book is the same regardless of its orientation, position, or location relative to the observer. It is thus unlikely that information about the spatial properties of the book will be stored for purposes of book-recognition, because these will change with the position of the observer. Unlike the perception-action system, which is viewer-centered, the recognition system encodes and stores those properties that are invariant across multiple perspective transformations of the object.

In this section, we review evidence that recognition begins at birth and that infants are endowed with perceptual decoding principles that exploit some of the most important regularities in the physical world. (This discussion is restricted to the processing of visual information because such information is most relevant to the proposed functional dissociation that guides this review.) These principles are initially available in implicit form and guide perception by constraining or privileging certain interpretations of the visual scene. As infants perceive the same information repeatedly, the stored representations derived from these experiences become increasingly rich and abstract (Eimas 1994). Perceptual and conceptual knowledge blend together in this framework, because stored representations are accessible for both recognition and reasoning (Spelke 1994).

Newborn Recognition of Objects

The traditional view is that infants are endowed with very simple capacities to look at objects—capacities that enable them to perceive the world piecemeal via fleeting images (e.g. Piaget 1954). This view acknowledges that recognition of some kind occurs early in life, but it is of a kind linked to previously produced actions and not to stored information about the world. Such a proposal is generally consistent with the development of those behaviors associated with the aforementioned perception-action system, but it does not generalize at all to the development of the object recognition system. Nevertheless, recent studies on object recognition reveal evidence of very early representation, beginning with recognition memory in neonates (Slater et al 1984, 1990a,b).

The habituation paradigm is foundational to the study of perceptual recognition by infants (Bornstein 1985) and thus deserves a brief overview. In this paradigm infants are presented with a specific stimulus for a number of trials until their attention declines. One reason that infants' attentiveness declines over trials is presumably that as they develop a stored representation of the stimulus it becomes less interesting. The encoding and storage of stimulus information are tested by presenting a novel stimulus following some criterion decrease in responding. If the infant's decline in responsiveness occurred because the first stimulus became familiar, then a novel stimulus should reinitiate responsiveness. Conversely, the novel stimulus should not produce an increase in responsiveness if the previous decline was simply a function of fatigue. Note that the sensitivity of this paradigm with very young infants is attributable to requiring only very simple responses, such as visual fixation.

The finding that neonates habituate to visual displays is provocative because it confirms that they begin to store perceptual information from their first encounters with the world. It is not necessarily the case, however, that this information is stored beyond the period of the study. Recently, Rovee-Collier (1995) introduced the concept of a "time window" to explain when and how new information would be integrated into memory. In essence, this theory predicts that repeated encounters with the same information over short periods increase the likelihood of long-term retention of that information.

Studies of neonates' face recognition capabilities suggest that the time window is functional from birth. Bushnell et al (1989) showed that neonates look longer at their mothers' faces than at strangers' faces, even when olfactory information was controlled by masking the odor of the mother. Walton et al (1992) reported that this preference was also observed when the faces were video recorded. More recently, Pascalis et al (1995) replicated this finding but showed that this preference was extinguished when women wore head scarves. The authors suggest that neonates store a representation of their mothers' faces in which the hairline and outer contour play a prominent role. This finding is consistent with the evidence that very young infants are biased toward the perception of low spatial frequencies, i.e. large-scale pattern information (Banks & Dannemiller 1987). As the spatial resolution of the visual system improves, infants respond more to the internal features of the face (de Schonen & Mathivet 1989, Morton & Johnson 1991).

These findings converge to show that infants begin to store frequently repeated perceptual information from birth. Presumably, this information is functionally significant and engages the infants' attention much more than other information available to them. Although the mother is typically specified by multimodal information, it is intriguing to find that neonates show recognition of modality-specific information. This finding is consistent with other evidence that perceptual information is stored in a modality-specific format by the recognition system (Bertenthal & Rose 1995). Less clear is the organization of the perceptual information stored by the neonate. We addresss this issue in the next section.

Implicit Knowledge of Objects

Before visual information is stored by infants, they must bind and/or segment it into units likely to be perceived when the same information is presented again. The complexity of most visual scenes makes this a formidable task for young infants. The infant's visual world may include a wide variety of objects ranging from blankets and stuffed animals to people, machines, and furniture. Most objects are not completely visible: Portions are occluded, boundaries are not always delineated, and the projective structure of this information changes continuously as infants and objects move. The first task for the infant is to ascertain which surfaces and features in the optic array comprise objects distinct from other objects.

Object segmentation is readily accomplished by adult observers, who organize the visual scene based on perceptual grouping principles, physical knowledge of objects, and past experience (Needham & Baillargeon 1995). Such grouping principles apply across many different contexts and situations. Recent research suggests that even young infants apply some of these same processes when viewing the visual world. For example, Spelke & van de Walle (1993) report that 3-month-old infants perceive two objects as distinct if they are separated in depth or move independently. By contrast, young infants do not perceive boundaries between objects that are stationary and adjacent, even if the objects differ in color, texture, and form. It is suggested that infants' perception of the spatial layout follows two specific principles or processing constraints. In essence, these principles assert that surfaces are perceived as connected if, and only if, they move together (principle of contact) or lie on a single object (principle of cohesion).

Additional studies reveal that young infants perceive the unity of partially occluded objects when the visible parts are seen to move together in a rigid fashion (henceforth referred to as "rigid motion") (Baillargeon 1987, Craton & Yonas 1990, Kellman et al 1986, Johnson & Nanez 1995, Slater et al 1990b). In an early study by Kellman & Spelke (1983), 4-month-old infants were repeatedly presented with a vertically oriented rod that moved horizontally back and forth behind a block that occluded the center of the rod. Once infants became habituated to this event, they were presented on alternating trials with two novel displays—a complete rod and a broken rod consisting of two collinear segments separated by a gap in the middle. Infants showed a significant increase in visual attention to the broken rod but not to the complete rod, suggesting that they perceived the previously presented partially occluded rod as a unitary object. Later studies revealed that any rigid translation of the partially occluded rod enabled 4-month-old infants to perceive the visible portions as unified (Kellman et al 1986); on the other hand, static grouping principles such as good continuation, collinearity, and similarity of texture or color were not sufficient to suggest unity (Kellman & Spelke 1983).

As infants grow older they begin to exploit additional regularities of the physical world in the process of segmenting objects. Needham & Baillargeon (1995) review a number of recent findings showing that infants by 8 months of age employ featural properties, such as color and shape, and physical constraints, such as the impenetrability of surfaces, to help them interpret ambiguous arrangements of objects in the visual scene. Their findings also suggest an important caveat to interpreting age-related changes in object segmentation. When infants were given prior experience with the objects that were displayed during the experiment, the correct perceptual response was shown at 4.5 months instead of at 8 months of age. Apparently, object segmentation processes interact with past experience when infants perceptually organize a visual scene.

The interplay between perceptual grouping processes and past experience is also illustrated by research on infants' perception of biological motions (Bertenthal 1993). These motions are depicted by points of light moving as if attached to the major joints and head of a person walking. Adult observers, who do not recognize static displays of such point-lights in any consistent way, recognize the moving point-lights as depicting a human form in less than 0.5 s (Johansson 1973, Bertenthal & Pinto 1994). Three- and five-month-old infants discriminate these same moving point-light displays from ones in which the temporal patterning of the lights are perturbed (Bertenthal et al 1987, Proffitt & Bertenthal 1990). It is conjectured that multiple processing constraints, including stored knowledge of the human form, contribute to the interpretation of these point-light displays (Bertenthal 1993, Bertenthal & Pinto 1994). This conjecture is supported by findings showing that 5-month-old infants do not discriminate point-light displays depicting unfamiliar objects, such as a four-legged spider, from a perturbed version (Bertenthal & Pinto 1993).

At a general level, the point-light display is similar to the partially occluded rod because both depict unitary objects that are more or less occluded. Nevertheless, an important difference between the displays is that the visible segments of the rod move rigidly, whereas the point-lights do not. The contact principle proposed by Spelke & van de Walle (1993; see above) exploits the rigid motions of spatially separated surfaces to organize the visual scene. In the case of biological motions, this principle will not suffice. Note that the object motions in these two displays correspond to very different categories of knowledge (i.e. physical vs biological), suggesting that different processing principles may be associated with different core domains (Leslie 1988, Carey & Spelke 1994).

One of the most important reasons that the preceding decoding principles appear so generalizable is that they mirror the physical constraints governing an object's behavior (Spelke et al 1992). A similar conclusion is reached by Shepard (1994) based on his research on adult perception of apparent motions. In the absence of any physically presented motion, the perceived path of an apparent motion is underspecified and must therefore reflect certain organizing principles in the visual system. Shepard contends that the visual system selects a particular motion from among the infinite set of possible motions according to the constraints of kinematic geometry, which govern the relative motions of rigid objects, or of local parts of nonrigid objects, during brief moments. According to Shepard, these physical constraints represent some of the most pervasive properties about the world that have endured throughout evolution; thus, natural selection should have favored genes that internalized these constraints as processing principles.

Computational research investigating infants' perception of structure from motion offers some additional support for the internalization of those physical constraints that contribute to the perception of objects. When perspective information is excluded from the display, a transforming 2-dimensional projection of a 3-dimensional stimulus is underdetermined. It is thus necessary for observers to implement additional processing constraints, such as a rigidity assumption, in order to extract a unique structure from the projection (Marr 1982). Arterberry & Yonas (1988) tested infants' perception of structure from motion by testing them with a 2-dimensional projection of a sphere filled with a random distribution of elements. When viewed statically, the 2-dimensional image appears ambiguous, but as soon as the elements begin to rotate, a rigid form is perceived—as long as the image is interpreted as the projection of a 3-dimensional rigid object. Arterberry & Yonas showed that infants as young as 4 months of age perceive 3-dimensional forms from 2-dimensional projections that change over time. Similar findings are presented by Kellman (1984) and Kellman & Short (1987). Collectively, these findings suggest that young infants are sensitive to some of the same processing constraints used by adults for perceiving 3-dimensional objects.

Explicit Knowledge of Objects

Theoretical opinion is divided over whether the processing constraints discussed above are induced from early perceptual experiences or correspond to innate cognitive representations of the physical world (Baillargeon 1993, 1995; Karmiloff-Smith 1992; Leslie 1988; Mandler 1988, 1992; Spelke 1994). In either case, an abstract representation of some kind guides the perception of objects by 3 months of age or younger. Moreover, recent findings suggest that these representations not only guide perception but also provide an early foundation for reasoning about the world. In other words, these abstract representations about the motions of objects are accessible to infants as explicit knowledge (Baillargeon 1993, 1995; Leslie 1988; Spelke et al 1992).

The principal evidence for this knowledge derives from occlusion studies in which inferences are required because the entire event is not visible. For example, Spelke et al (1992) tested 2.5–4.5-month-old infants' reasoning about the continuity and solidity of objects by habituating them to various events. In one experiment, an initially visible ball was dropped behind a screen and then the screen was raised to reveal the ball on the floor of the stage. After infants became habituated to this event, a brightly colored surface was added above the floor, the screen was lowered to cover both surfaces, and then the ball was dropped again. On alternating trials the screen was raised to reveal a ball on the new surface or on the floor of the stage. Adult observers reason that the former event is (covert manipulation aside) impossible because it would require the ball to pass through or jump over the upper surface. Such movements would violate both the continuity principle of objects (i.e. objects follow one continuous path over space and time) and the solidity principle (i.e. the parts of distinct objects may never coincide in place and time). Apparently, infants appreciate these principles, because they paid considerably more visual attention to the impossible event than to the possible event. Additional experiments by Spelke et al (1992) and by Baillargeon (1993) converge to show that young infants reason about the continuity and solidity of objects involved in simple physical events.

Certain other physical concepts, such as gravity and inertia, are not understood by infants until close to the end of their first year (Spelke et al 1992, Spelke et al 1994). This finding highlights an important difference between the perception-action system and the object-recognition system. Research on young infants' reaching for moving targets (reviewed above) suggests that they are implicitly sensitive to gravity and inertia by 5 to 6 months of age;

otherwise, it is difficult to imagine how they could successfully anticipate the future position of moving targets. This implicit knowledge is not generaliz able, however, because it is encapsulated in the action and is thus not represented in a format accessible by the cognitive system. By contrast, knowledge about gravity and inertia that is represented by the object-recognition system will generalize across situations once it is stored as a representation.

The conclusion that young infants reason about physical events is contested by some theorists (e.g. Fischer & Biddell 1991, Oakes & Cohen 1995, Siegler 1993). In evaluting this research, it is important to distinguish between the evidence for infants' reasoning and the conclusion that these results reflect innate theories of the physical world. The empirical evidence that reasoning occurs is much more defensible than the evidence for an innate core of knowledge, especially because most studies of infants' physical reasoning focus on infants 3 months old or older. Resolution of this issue requires an explanation of how core knowledge about the physical world (e.g. about the continuity and solidity of objects) develops from perceptual information (Spelke 1994). This is a daunting requirement, but preliminary ideas are beginning to appear in the literature.

Baillargeon (1995) suggests that the development of physical knowledge reflects a highly constrained learning mechanism that processes the available perceptual information. Regrettably, the details of this learning mechanism are vague, although some of the predictions are not. Baillargeon claims that infants first learn to encode the causal properties of a physical event, such as a collision, at a very simple level and then begin to encode both qualitative and quantitative variables about the event. For example, a series of experiments by Kotovsky & Baillargeon (reviewed in Baillargeon 1995) reveals that 2.5-month-old infants expect a stationary object to be displaced when hit by a moving object, but it is not until 5.5–6.5 months of age that infants recognize that a stationary object should be displaced further by a larger than by a smaller moving object. It is conjectured that infants will begin to encode other variables, such as mass, speed, and distance, following additional experience with relevant events (Baillargeon 1995).

Object Recognition Is Domain Specific

An important implication of the preceding theory is that infants' knowledge of physical events develops piecemeal and not all at once. Some object properties, such as size, are more easily detected than others, such as mass, and thus conceptual knowledge of the physical world develops gradually as it is tutored by experience. A related developmental trend is that infants appear to use spatio-temporal information to specify the identity of objects prior to individuating these objects on the basis of featural information (Cohen & Oakes 1993, Xu & Carey 1995). Even though infants are sensitive by 6 to 7 months of age to launching events and other events involving spatio-temporal continuity (Baillargeon 1993, Leslie & Keeble 1987, Oakes 1995), recent evidence suggests that they do not detect the individuating properties of objects in these dynamic events until 10 to 12 months of age (Xu & Carey 1995). Evidence for this latter conclusion is somewhat suspect, however, because infants can perceptually categorize certain basic kinds of objects by 3 months of age (Quinn & Eimas 1986). Perceptual categorization requires that infants both distinguish between and generalize about objects based on specific features; thus, these categorization findings suggest that young infants do represent identifying features of objects.

The apparent discrepancy between the findings cited aboved may be explained by noting that evidence for perceptual categorization of objects prior to 10 months of age is restricted primarily to animate objects, such as people and animals (Eimas & Quinn 1994, Eimas et al 1994, Quinn & Eimas 1986, Quinn et al 1993). By contrast, studies investigating infants' knowledge of object motions and causal interactions involve inanimate objects, such as cars and blocks (e.g. Baillargeon 1995, Leslie 1988, Oakes & Cohen 1995). Recent neuropsychological evidence suggests that adults represent and perceptually process living and nonliving things differently (Farah 1992). In general, living things are represented holistically whereas nonliving things are represented by the relations among their parts. The origins of these differences may be present early in development, a possibility that would help to explain the finding of different representations for animate and inanimate objects by infants.

Although such a reconciliation between findings is somewhat speculative, it is certainly consistent with recent proposals that conceptual knowledge is present early and organized by core principles of domain-specific knowledge—e.g. people, objects, number (Cary & Spelke 1994, Wellman & Gelman 1992). One explanation for early differences that emerge between core domains follows from the proposal by Eimas (1994) that categorical knowledge emerges from a progressive abstraction of the stored perceptual information. Presumably, the perceptual properties that are initially encoded and stored differ as a function of the task being performed along with these processes, and thus initial knowledge about people and objects will differ because our early interactions with these entities are so different.

CONCLUSIONS

The research discussed in this review is noteworthy for many reasons, but three are highlighted. First, recent findings on newborns reveal that they are considerably more competent than once believed. Neonates are endowed with much more than reflexes or fixed action patterns. Their actions are goal directed and spatially coordinated, even though they lack consistency and are often obscured by other factors, such as posture. Also, neonates show recognition memory from birth, and by 3 months of age infants reason about events that are perceptually occluded. During the first year of life, these actions and representations become more accessible and more generalizable, but the clear message from the recent research is that the representations available to infants are not directly a function of the coordination and internalization of actions.

Second, this review was organized by the proposal that perception and action and object recognition and representation are functionally dissociable processes that follow different developmental trajectories. Although it is premature to offer specific predictions based on this proposal, it is possible to offer a few generalizations regarding the development of both systems.

The findings on the development of perception and action concur with the earlier characterization of the perceptual control system as functioning in real time with little explicit reference to past experience. Perceptually controlled actions are modularly organized and not represented in a form that is recalled or used to guide the production of other responses. It is sufficient that infants perceive where they are and what they are doing. All that matters is the present fit between the infant and the environment. Past experience does of course contribute to the development of these systems in the form of perceptual learning. With exploration of their own actions and the environment, infants show increasing sensitivity to perceptual changes and finer control of actions that are guided by this information. In essence, then, learning is implicit or procedural; it is elicited by context, not by recall of explicit information about how to coordinate sensorimotor behaviors.

By contrast, research on the development of object recognition confirms that even young infants represent defining features and physical constraints that specify the unity and boundedness of objects. It is significant that these defining properties, such as structure from rigid motions, are invariant across perspective transformations. This invariance increases the likelihood that objects are recognized in new orientations and contexts. The representations necessary for object recognition are organized as domain-specific concepts that accumulate new perceptual information over time. Perceptual experience is the principal engine by which representations become more abstract and differentiated. These representations not only guide perceptual processing, but also are available in explicit form to guide infants' reasoning about the most fundamental and frequently encountered properties of their world.

The third and last conclusion emerging from this review concerns the generalizability of specific research findings. It is always advisable to exercise caution when generalizing between different contexts and measures (Thelen 1995), and the current review offers new reasons for such caution. As discussed repeatedly in this review, competencies manifested by one response system, such as eye movements, are not necessarily manifested by another system, such as reaching, at the same age. An additional complication becomes evident when inferring conceptual competencies, e.g. object permanence, from various response measures, because the development of conceptual knowledge and systems are mediated by dissociable processes that follow independent developmental trajectories. Thus, the development of a specific response measure could easily lag behind or otherwise misrepresent the development of a specific concept.

The proposed functional dissociation between perceptuomotor and object recognition processes is not meant to imply that these two processing systems are completely independent. Clearly, thought and action interact at some level, and developmental changes in one system surely affect the other. An important research task for the future is to investigate when and how new representations and actions are coordinated in the process of development.

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Annual Review of Psychology
Volume 47, 1996

CONTENTS