13 James Gibson's Ecological Approach to Locomotion and Manipulation

Development and Changing Affordances

Karen E. Adolph, Justine E. Hoch, and Ori Ossmy

Action Is Integral to Perception

One of James Gibson's profound insights was that perception and action are functionally linked. Indeed, in a book purported to be about perception, every chapter of *The Ecological Approach to Visual Perception* is permeated with references to action.

Perception-Action Reciprocity

In Gibson's (1979/2015) view, perception and action are interdependent: "We must perceive in order to move, but we must also move in order to perceive" (p. 213). The primary function of perception is to guide action adaptively. Perceiving possibilities for action (or "affordances" in Gibson's terminology) requires humans and other animals to detect relations between the self and the world (see Wagman, Chapter 8, in this volume). Reciprocally, motor actions generate perceptual information. Exploratory movements such as looking with the head and eyes or feeling with hands, whiskers, or antennae are intended to "forage" for perceptual information (see Franchak, Chapter 12, in this volume). Performatory actions (e.g., catching a ball), and spontaneous movements (e.g., fidgeting) are not intended to generate perceptual information, but do so nonetheless.

In everyday activities, perception and action are seamlessly intertwined. Tiny swaying movements while sitting or standing yield information about postural stability and body position relative to the environment. Locomotion generates information about the body's dimensions, abilities, and location relative to the layout of surfaces. Grasping an object produces information about the acting limb relative to the acted-on object. Moreover, the coupling between perception and action creates an ongoing flow of information, blurring the boundary between remembering and planning (see Thomas, Riley, & Wagman, Chapter 14, this volume). Every movement creates perceptual information about its consequences and about what to do next. Thus, action ties perception to a history of the recent past and provides a roadmap into the near future.

Basic Actions

Gibson highlighted four types of basic actions: (1) postural actions, (2) exploratory actions, (3) locomotion, and (4) manipulation. Each type plays a prominent role in his theory. Gibson devoted many pages, and in the case of visual exploration and locomotion/manipulation, whole chapters to their discussion. In Gibson's treatment, the four types of basic actions are interconnected. Posture and exploration, for example, support and guide locomotion and manipulation.

Postural actions are the foundation for every other kind of action (see Reed, 1982b). Posture provides a stable base for moving the torso, head, and eyes during visual exploration and for moving the limbs during locomotion and manipulation. Postural actions also keep the animal oriented to gravity and the medium (air, water, or ground) in or on which it moves.

Exploratory actions are movements intended to generate information for perceptual systems (E. J. Gibson & Pick, 2000). Exploration can guide upcoming actions, aid knowledge acquisition, or support playful activity (E. J. Gibson, 1988). Turning the head creates motion parallax and optic flow, and brings new parts of the self and environment into view. Wielding an object or palpating a surface creates torques at the joints and deformation and stretching of flesh and skin, thereby revealing information about object and surface properties.

Locomotion involves moving the whole body through the environment. It can be accomplished with a tremendous variety of means. Trotting dogs create forces against the ground with their limbs; swimming fish sweep their tails back and forth through the water; and flying insects beat their wings against the air (Dickinson, Farley, Full, Koehl, Kram, & Lehman, 2000). Even during a single observation, animals exhibit a variety of means of locomotion (Adolph & Berger, 2015). Human infants, for example, produce multiple patterns of interlimb coordination when crawling.

Manipulation involves acting on objects and surfaces in the environment. Humans normally do it with their hands, but when their hands are occupied, adults can use a hip to bump open a door or their neck and chin to hold a package. People without hands can learn to use their feet to thread a needle, play the piano, light a cigarette, or make a sandwich. Non-human animals use necks, beaks, and mouths to manipulate and transport objects.

In contrast to typical approaches (e.g., Schmidt & Lee, 2011), Gibson's ecological approach to locomotion and manipulation is not merely about the well-studied human activities of walking and reaching. Instead, Gibson's theory is broad enough to cover a wide range of animals with a wide range of perception-action systems performing the wide range of behaviors that the species evolved to perform. His theory is robust enough to explain perceptual control of action in a wide range of environments. It applies to natural, uncultivated environments but also generalizes to the designed world of manufactured artifacts and built environments—actions like sitting on chairs, using binoculars, driving cars, landing planes, and using tools such as hammers (see Pagano & Day, Chapter 3, in this volume). However, because Gibson's primary focus was on perceptual control of functional action, his approach is less suited to explain many popular topics in human perception research such as visual processing, color perception, covert attention, face perception, and optical illusions. Indeed, many classic and current perceptual phenomena—especially those arising from artificial laboratory tasks—are not well handled by his theory.

Exploration, Development, and Changing Affordances

Despite Gibson's broad treatment of perceptual guidance of action, a critical factor is conspicuously absent from *The Ecological Approach*—development.

Contributions of the Susan Linn Sage Professor

The omission of development is striking because Gibson's wife and valued colleague, Eleanor Gibson, was a renowned developmental scientist, member of the National Academy of Sciences, fellow of the American Academy of Arts and Sciences, and author of *Principles of Perceptual Learning and Development* (1969). Years before *The Ecological Approach* was published, Eleanor Gibson was considered a world expert in perceptual learning and development (Adolph & Kretch, 2015). As J. Gibson wrote in the preface of his book:

> Above all there is the Susan Linn Sage Professor of Psychology at Cornell who worked very hard on this book, even if she did not write it. She is married to me, and we share responsibility for important decisions. Any errors in this book that remain are her fault as much as mine.
>
> (p. xii)

By 1979, when *The Ecological Approach* was published, many methods were available to study perceptual and motor development in infants. In fact, two decades before its publication, Eleanor Gibson devised one of the most famous paradigms in developmental psychology—an illusory drop-off dubbed a "visual cliff"—to test depth perception and affordance perception in infant humans and other animals. The apparatus is a glass-covered table with a patterned surface flush beneath the glass on the "shallow" side and far beneath the glass on the "deep" side (Adolph & Kretch, 2012; E. J. Gibson, 1991; E. J. Gibson & Walk, 1960). Although the visual cliff is discussed in several chapters of *The Ecological Approach*, development is not.

Development and Changing Affordances

Albeit absent from *The Ecological Approach*, development is integral to Gibson's proposal that perception functions to detect affordances for action. Animals' bodies and environments develop, and these changes alter the body-environment relations that make particular actions possible or not. Gibson recognized that affordances for locomotion and manipulation differ across species. Lightweight water bugs with hydrophobic legs can walk on water, but heavy animals or insects without hydrophobic legs cannot. However, affordances also differ depending on each animal's level of development. An 18-cm drop-off (the height of a typical stair) is an impossibly high cliff for a newly walking infant. With developmental changes in leg length, muscle strength, and balance control, it becomes a challenging but navigable obstacle for a more accomplished toddler, a big step for a child, a trivial stair for a young adult, and a challenge again for an elderly adult.

Indeed, development creates new affordances for locomotion and manipulation (for reviews, see Adolph & Hoch, 2019; Adolph & Robinson, 2015; E. J. Gibson, 1988). Before infants can sit or stand, much of the world is out of sight and out of reach. Head-mounted eye tracking shows that in a prone position, infants primarily see the ground in front of their hands. They cannot see objects across the room or lift their head to see their caregiver's face. Object manipulation is difficult because infants must prop themselves on one hand to grasp and explore objects with the other hand. After infants can sit and stand, the whole room comes into view. In a sitting or standing position, both hands are free to manipulate objects, facilitating learning about object properties. The ability to walk opens up a new world of affordances. Compared with experienced crawlers, novice walkers spend more time in motion, take twice as many steps, and travel three times the distance. Given their upright posture and propensity to move, walkers go to more places, access more distal objects, carry objects more frequently, and bring objects to their caregivers. In short, walkers move, see, explore, and interact more (Adolph & Tamis-LeMonda, 2014).

What Is Learned? Exploratory Actions, Information "Pickup," and Perception of Affordances

Gibson acknowledged the importance of learning and exploration throughout *The Ecological Approach*. As the explorer learns to discriminate or, in his terminology, "pick up" the relevant information that specifies an affordance, exploratory activities become increasingly efficient. But Gibson was confused about whether infants must learn to perceive affordances of drop-offs and other basic features of the environment. He wrote: "the basic affordances of the environment are perceivable ... without an excessive amount of learning" (p. 134). In fact, Gibson thought the perception of basic affordances was a better candidate for nativism than abstract knowledge: "As for innate versus learned perception, it is much more sensible to assume an innate capacity to notice falling-off places in terrestrial animals than it is to assume that they have innate ideas of mental concepts of geometry" (p. 151). Indeed, if any knowledge were innate, it should be knowledge that ensures an animal's survival—"don't fall off a cliff!" Nevertheless, Gibson's assumption was wrong. Human infants do not have an innate capacity to perceive a large drop-off as a falling-off place (Adolph & Kretch, 2012). Neither do kittens, puppies, infant monkeys, and other animals that cannot walk at birth. But Gibson knew this too. He also wrote, "Perceiving the meaning of an edge in the surface of support, either a falling-off edge or a stepping-down edge, seems to be a capability that animals develop. This is not abstract depth perception but affordance perception" (p. 160). It seems that at the time of Gibson's writing, he did not fully appreciate the contributions of the Susan Linn Sage Professor.

In the years since *The Ecological Approach* was published, developmental researchers have learned much about age- and experience-related changes in perception of affordances for locomotion and manipulation. Thus, for the remainder of this chapter, we focus on examples of developmental research conducted from an ecological point of view. Many findings support Gibson's ideas about mature visual guidance of basic actions. However, work with human infants also reveals a protracted process of learning to perceive affordances and guide actions adaptively as infants acquire locomotor and manipulative skills.

Affordances for Locomotion

The Ecological Approach outlined several important functions of vision for guiding locomotion: keeping balance, controlling collision, steering, navigating a cluttered environment, and coping with variations in the ground surface. However, Gibson did not acknowledge that visual guidance of locomotion improves with development. Moreover, Gibson's focus on vision made short shrift of other sources of information. Haptic information, for example, is important for keeping balance, and haptic exploration is critical for detecting variations in surface friction and rigidity (for a review, see Adolph & Joh, 2009).

Maintaining Balance

While upright, the body is always in motion. Even during quiet stance, the body sways within the base of support. To maintain balance, a sway in one direction must be met by a compensatory sway in the opposite direction. As Gibson supposed, optic flow is important for balance control. When visual, haptic, vestibular, and muscle-joint information for body sway are in conflict, visual information trumps the rest. Adults, for example, adjust their standing posture in response to simulated optic flow in a "moving room" (Lee & Lishman, 1975). Forward and backward movements of the room's side walls create a lamellar flow structure in the visual periphery. The optic texture elements streaming in parallel along the sides of the field of view simulate the visual information for body sway (like the false perception of self-motion when an adjacent car or train starts moving). In response, adults induce compensatory sways in the opposite direction (see Shaw & Kinsella-Shaw, Chapter 6, in this volume; Smart, Hasselbrock, & Teaford, Chapter 10, in this volume). Older children (3–6 years) do likewise. Compensatory responses in toddlers are so strong that they often step, stagger, and fall (for a review, see Adolph & Berger, 2015). Although precrawlers do not respond to peripheral lamellar flow in the moving room, after 15 days of experimentally-boosted locomotor experience propelling themselves around in baby go-carts, their responses are more similar to those of infants who are independently mobile.

Of course, in everyday settings, vision is not the only source of information for postural sway. As Gibson recognized, multiple sources of information redundantly specify the body's position in space. Indeed, merely the light touch of a toddler's hand resting on a horizontal surface provides haptic information for postural stability (for a review, see Adolph & Berger, 2015). Although touching a surface does not mechanically support infants' weight, it reduces postural sway, and walking experience improves toddlers' ability to benefit from a light touch.

Controlling Collision

In addition to lamellar flow, postural sway and locomotion also create radial optic flow. As Gibson suggested, optic texture elements streaming outward from a central point of expansion specify the direction of heading, and can guide locomotion toward a goal, or around an obstacle (Warren, 1998). The rate of change in the expansion of optic flow specifies the time to contact, so collisions can be softened or avoided (Lee, 2009). Gibson pointed out that an approaching obstacle (e.g., a ball on a collision course with the observer's face) expands in the observer's field of view. It also hides more and more of the background vista until the obstacle fills the field of view. In contrast, a receding obstacle (e.g., a car speeding away) progressively reveals more and more of the background scene. Likewise, as an observer approaches an obstacle, more and more of the background is occluded, but as an observer approaches an aperture, more and more of the background is revealed inside the opening.

Long before infants are independently mobile, they distinguish an approaching obstacle from an aperture. They blink their eyes and press their heads backward in response to a looming obstacle but not in response to a looming aperture (for a review, see Adolph & Berger, 2015). Infants also take the path of the approaching obstacle into account and distinguish objects on a head-on collision course from those that will pass safely to one side (Schmuckler, Collimore, & Dannemiller, 2007). However, younger infants use information about the size of the visual angle created by the approaching object; they wait until the visual angle is a certain size and as a consequence they blink too late to protect their eyes from objects on a fast collision course (Kayed & van der Meer, 2007). In contrast, older infants use information about the time to contact. Because this information is available earlier in the object trajectory, they can respond to faster accelerations (see van der Meer & van der Weel, Chapter 7, in this volume).

After infants become mobile, they slow down and turn their bodies while approaching apertures (for reviews, see Adolph & Berger, 2015; Adolph & Robinson, 2015). But people of all ages and sizes, from infants to elderly adults, attempt to squeeze through apertures too narrow to fit their bodies. Pregnant women adjust their judgments to their growing bellies, but they also attempt to navigate apertures that are slightly too small. Apparently, attempting to fit is more compelling than the penalty of entrapment. Unlike adults, however, infants repeatedly attempt to navigate apertures so small that they can only wedge an arm or leg into the opening.

Coping with a Cluttered Environment and Variations in Terrain

Locomotion gets an animal from one place to another, but the everyday environment is rarely free of obstacles. The landscape is littered with hills, holes, stairs, and ledges. The ground can be slippery, sloping, rigid, or unstable. Thus, locomotion requires coping with variations in the terrain. For Gibson, a particularly illustrative example is the difference between a cliff and a step. A cliff is a drop-off that is large relative to an animal's size and capabilities. A step is a drop-off that is small relative to the animal's size and capabilities. Moreover, "a falling-off edge is dangerous, but a stepping-off edge is not" (p. 149). The Gibsons disagreed about whether the ability to differentiate cliff from step develops. Indeed, both Gibsons told their students about a family trip to the Grand Canyon in which James Gibson insisted that their young children would naturally avoid the drop-off, but Eleanor Gibson worried that perceiving risk at the edge requires learning (Adolph & Kretch, 2012).

In fact, human infants and other altricial animals require weeks to months of locomotor experience before they can tell the difference between safe and risky ground (for reviews, see Adolph & Hoch, 2019; Adolph & Kretch, 2012; Adolph & Robinson, 2015). When babies first begin crawling and walking, they plunge right over the edge of a cliff. On a *visual* cliff, the glass surface ensures infants' safety. On an *actual* cliff, infants are harnessed or an experimenter catches them when they fall. With each week of crawling and walking experience, infants' judgments become increasingly accurate, until they can discern the difference between gradations of step and cliff (0–90 cm) within 1 cm of accuracy. Similarly, novice crawlers and walkers fall repeatedly over the brink of impossibly steep slopes. Infants' judgments improve with locomotor experience until they can distinguish possible from impossible slopes (0–50°) within 2° of accuracy. Experienced infant walkers even calibrate their perception of affordances to take experimentally-induced changes in their bodies into account—lead-weighted shoulder packs or Teflon-soled shoes. Likewise, experienced crawlers and walkers precisely detect possibilities for locomotion across bridges and ledges varying from 0–60 cm in width.

However, infants show no evidence of transfer over the developmental transition from crawling to walking. The same experienced crawlers who perceive affordances with exacting precision, repeatedly attempt impossibly large drop-offs and steep slopes when they face the precipice as novice walkers. More generally, learning to perceive affordances does not transfer from earlier developing postures to later developing ones. The same infants who precisely perceive affordances for reaching over gaps (0–90 cm) in an experienced sitting posture repeatedly attempt impossibly large gaps in a novice crawling posture. Whereas experienced cruisers accurately detect affordances for cruising over gaps (0–90 cm) in a handrail they hold for support, they do not perceive the impossibility of cruising over gaps in the floor beneath their feet. Novice walkers also step straight into gaps in the floor.

Thus, infants show separate learning curves for sitting, crawling, cruising, and walking and no evidence that learning is faster the next time around (for a review, see Adolph & Robinson, 2015). Why no transfer? Why does sitting experience only teach infants to perceive affordances for sitting, crawling experience only teach infants to perceive affordances for crawling, and so on? New modes of action create new affordance relations. The body-environment relations for crawling over a precipice, for example, are entirely different from those for walking. They involve different body parts producing different forces in different configurations. The exploratory actions that generate information for affordances are also different. For each posture in development, infants must learn all over again to generate, detect, and use perceptual information about body-environment relations to perceive affordances for balance and locomotion.

Exploration in the Service of Locomotion

On Gibson's account, perceptual information is needed to guide locomotion adaptively, and exploration is needed to generate the required information. Like locomotion and other performatory actions, exploratory actions also must be planned and controlled. Because exploration in the service of locomotion plays out in a temporal and spatial sequence as animals approach an obstacle or destination, guiding the current exploratory action requires perceptual information obtained by prior exploration (Adolph, Eppler, Marin, Wiese, & Clearfield, 2000).

Moreover, exploratory movements have different costs in terms of time, effort, and potential risk (Kretch & Adolph, 2017). Information collected from peripheral vision is "free" because the eyes pick up visual information in the course of locomotion. However, it takes effort to move head and eyes to look at an obstacle. Adults minimize costs by using peripheral vision whenever possible. Head-mounted eye tracking shows that adults can step up, down, and over small obstacles using peripheral vision alone (Franchak & Adolph, 2010). But on rough terrain, adults continually look at the ground, and direct their gaze to the foothold two steps ahead (Matthis, Yates, & Hayhoe, 2018). By dint of their smaller stature, infants and children see the ground closer to their feet through peripheral vision. Although infants and children direct their gaze to obstacles more frequently than do adults, they can also navigate small obstacles using only peripheral vision (Franchak, Kretch, Soska, & Adolph, 2011).

Haptic exploration is more costly than looking, and a search for alternative methods by testing various options is more costly still. Whereas visual exploration can occur from a distance, haptic exploration and testing alternatives require proximity to the potentially risky surface. To explore by touching, observers must modify their gait as they approach the obstacle, interrupt locomotion by stopping at the edge, and maintain balance while poking out a "feeler" (e.g., hand or foot) to probe the surface. The more closely the exploratory action approximates the locomotor action, the more useful the information, but the greater the risk of injury.

Infants minimize costs by ramping up exploratory actions based on information obtained from previous exploratory movements (Adolph et al., 2000; Kretch & Adolph, 2017). For example, as infants approach a bridge spanning a precipice, head-mounted eye tracking shows that their first sight of the obstacle is through peripheral vision. If the bridge is wide, they run straight across. But if the bridge is narrow, they direct a quick glance at the obstacle. If this glance suggests further information is needed, infants slow down and engage in more costly haptic exploration by poking a foot out to feel the bridge or take tiny steps with their feet just over the edge. If haptic information suggests crossing to be safe, infants carefully inch their way to the landing platform. But if crossing still feels risky, they test alternative strategies by shifting positions (e.g., from standing to squatting, crawling, backing, and sitting) before they discover a suitable course of action. If infants cannot find an alternative, they avoid going.

As Gibson noted, animals misperceive affordances for locomotion when they fail to detect the relevant information from a distance: Birds fly into glass windows and people trip over unseen impediments on the ground.

Visual information can reveal upcoming changes in surface layout such as elevations, slopes, or the narrowing of the path, and thereby instigate the appropriate sequence of exploratory movements. However, information about variations in friction and rigidity can only be detected through direct contact with the ground surface (Adolph & Joh, 2009; Adolph & Robinson, 2015). For example, the visual information available from a shiny Teflon surface, rippling waterbed, or lumpy foam pit is not sufficient to alert the observer that the surface may not afford locomotion. Shine is not a reliable cue for slip, and lumps are not a reliable cue for deformability because the properties relevant for locomotion only emerge when the supporting limbs contact the ground surface (Adolph & Joh, 2009). Without additional haptic information, non-human animals and people of all ages step straight onto slippery, squishy, or flimsy surfaces—and fall (Adolph & Berger, 2015).

Affordances for Manipulation

In Gibson's view, understanding perceptual control of manual actions is especially challenging because "the uses of the hands are almost unlimited" (p. 224). The "five-pronged squirming protrusions" at the end of the human arm can be used to grasp objects, open lids, eat food, and caress a child (p. 214). *The Ecological Approach* gives equal attention to manipulation of natural objects (e.g., rocks and leaves) and manufactured artifacts (e.g., scissors, cabinets, blankets). Gibson's ideas about affordances for manipulation inspired a wave of research in human factors and product design (Norman, 2013; see Pagano & Day, Chapter 3, in this volume). In particular, Gibson highlighted the use of tools to extend manual capacities. While in use, the tool becomes an extension of the body; when it is put down, it reverts to being an object. Thus, Gibson argued that tool use blurs the boundary between body and environment.

However, Gibson's insights about manual action gave short shrift to development; he did not discuss the foundational role of posture in supporting manipulation; and he over-emphasized the role of visual kinesthesis in reaching. Finally, Gibson's approach to prospective control—using perceptual information to plan future actions—works best when the necessary information is currently specified in the ambient array (e.g., catching a ball). His approach is less tenable for multi-step actions that require higher-order planning (when initial actions required to accomplish the end goal are not specified by currently available perceptual information).

Posture Provides the Foundation for Manipulation

Gibson noted that locomotion can support manual activity—many trips toward objects terminate in reaching and grasping, and locomotion is often used to transport objects. But posture is even more critical than locomotion to support manipulation (for reviews, see Adolph & Berger, 2015;

Adolph & Hoch, 2019; von Hofsten, 2003). Lifting an arm to reach displaces the body's center of mass. To avoid disruptions to balance, the torso must anticipate the arm movement. More generally, the postural and manual systems must collaborate so that actions can be timed and controlled prospectively. For infants, this is a difficult task. Without sufficient coordination and strength to stabilize the body, infants' heads flop over and their torsos collapse as they try to initiate a reach from a sitting position. Infants can reach with one hand only after they learn to prop themselves up on one arm in a prone or tripod position, and they can reach with two hands free only after they learn to sit independently.

Exploring an object in hand is also dependent on posture. While sitting with both hands free, infants can explore an object by fingering the surface to generate information about shape and texture; they can rotate it and transfer it between hands to reveal its three-dimensional form; and they can alternate between mouthing and looking to exploit the sensitivity of the mouth and tongue. But while prone, such exploratory procedures are hampered because one hand is occupied with propping up the head and chest. While supine, mouthing predominates because infants' arms are too weak to hold the object in front of their eyes.

Planning a Reach in the Light and in the Dark

As Gibson noted, vision plays an important role in reaching. The sight of a desirable object provides an impetus to reach. Neonates and older infants extend or flap their arms more frequently in the presence of a visually salient object than when no object is present (for reviews, see Adolph & Berger, 2015; von Hofsten, 2003). The sight of the hand is also attractive to young infants. Neonates turn their head to keep their hand in view. The early tendency to coordinate eyes and arms and to extend the arms toward looked-at objects likely provides a developmental basis for later visual-manual exploration and visually guided reaching. But to what extent does the concurrent sight of the object and hand guide a reach? Of course, Gibson was correct that looking at the hand as it approaches an object causes "the optical minification of the squirming silhouette of the hand … while optical magnification specifies flexion of the arm" (1979/2015, p. 113). However, Gibson overemphasized the role of visual kinesthesis—seeing where the body parts are and what they are doing relative to things in the environment—in guiding a reach to a target. In his words, "reaching is an elongation of the arm-shape and a minification of the five-pronged hand-shape until contact occurs" (p. 224), but that is not the way that reaching typically happens—even in infants.

Like Gibson, the first researchers to study the development of reaching conceived it as a process of continually matching the sight of the hand to the sight of the target (for reviews, see Adolph & Berger, 2015; Adolph & Robinson, 2015; Smitsman & Corbetta, 2010). Indeed, at first blush, the primacy of visual kinesthesis in infant reaching seems a reasonable supposition. Infants' first reaches are jerky and inefficient with multiple changes in direction and speed; over development, the reaching path becomes straighter and smoother. Thus, researchers inferred that jerky reach trajectories result from online corrections and overcorrections as infants continuously track and adjust the location of the hand relative to the target. But infants do not need to see their hands to reach. Infants reach for objects in the light at the same age that they reach for glowing objects in the dark, and early attempts at reaching are jerky and erratic regardless of the lighting. Jerky infant reach trajectories are likely due to the biomechanical and dynamic characteristics of arm movements, not a product of visual guidance and correction.

Although normally not necessary for online guidance of reaching, sight of the hand and target facilitates more precise manual actions (Berthier & Carrico, 2010). Seeing hand and target, for example, improves infants' control of their hand trajectory as they reach for a tiny morsel of food. Moreover, getting the hand to the object only solves part of the problem of object prehension. After the target is located and the arm is on its way, grasping the object requires configuring the hand relative to object properties. Visual kinesthesis facilitates grasping an object as Gibson proposed. Infants use concurrent visual information about hand and object to adjust their hand to the object's shape, size, and orientation (for reviews, see Adolph & Berger, 2015; Adolph & Robinson, 2015). Very young infants bump their hand into the object before opening their fingers to grasp it. Older infants retrieve objects with a whole-handed power grip, and later use a precision grip (index finger and thumb) to grasp small objects. By 10–12 months of age, infants adjust the space between finger and thumb—grip aperture—as their hand approaches the object. For large or unwieldy objects, infants use visual information to decide whether two hands are needed, and if so, they scale the space between their hands to the object's size. When objects are irregularly shaped, infants aim their hands closer to the center of mass. Eventually, children's manual actions are so precise that they switch from a one- to a two-handed grasp when the size of an object exceeds the size of their grip aperture. As Gibson noted,

> Long before the child can discriminate one inch, or two, or three, he can see the fit of the object to the pincer like action of the opposable thumb. The child learns his scale of sizes as commensurate with his body, not with a measuring stick.
>
> (1979/2015, p. 224)

Planning for Future Manual Actions

Gibson argued that optical information specifies both current and impending events—events that begin in the present and will continue into the near future (e.g., imminent contact with a looming object). Gibson also argued that such information provides the basis for controlling action prospectively (e.g., dodging a thrown rock or catching a thrown ball). Empirical evidence of two different kinds suggests that the ability to use visual information to anticipate the future location or orientation of a moving object develops in infancy (for review, see von Hofsten, 2003). First, infants successfully intercept a moving target by putting their hand into the object's path or appropriately orienting their hand to grasp a rotating rod. Second, if the trajectory of a moving object abruptly changes, infants move their hand to where the object should have been rather than to its new, unanticipated location.

For manual actions involving moving objects and/or moving observers, timing is critical. Younger infants attempt to catch a moving target by "chasing" it with the near hand as it moves past and then "catching" it with the far hand as it moves into the far side of reaching space (Fagard, Spelke, & von Hofsten, 2009). Older infants lift their far hand to intercept the object as it approaches. Moreover, the visual information that infants use to intercept moving objects changes over development. Younger infants use information about object distance or speed to time their reach (Kayed & van der Meer, 2009). Older infants perceive the time to contact the object. Information for time to contact is more efficient because it ensures sufficient time to lift the arm and orient the hand (see van der Meer & van der Weel, Chapter 7, in this volume).

When the infant is moving and the target is stationary, the timing of postural, visual, and manual systems must be precisely coordinated. For example, to retrieve a target while spinning 360° on a motorized chair, infants must first turn head and trunk to visually locate the object, then plan arm movements to ensure that their hand arrives at the object's location, and finally shape the hand to intercept and grasp the object before they spin past. Infants and adults share a common spatiotemporal sequence of postural-visual-manual coordination, but infants perform this sequence more slowly than adults (Rachwani, Golenia, Herzberg, & Adolph, in press). For infants, greater postural control predicts faster planning of manual actions.

Some manipulative actions involve multiple steps (e.g., pick up fork, spear bite of broccoli, and bring fork to mouth). Although Gibson did not explicitly address multi-step actions, his approach can explain such behaviors. Each step in the sequence generates information for the next step, so the multi-step action unfolds in an ongoing stream of perceptual information. Older infants, for example, fit a square block into a square aperture by first grasping the block and then smoothly aligning the block as it approaches the aperture so that the fit is seamless and uninterrupted (for a review, see Lockman, Fears, & Jung, 2018). Younger infants do not preadjust the orientation of the block during approach; instead, they bring the block to the aperture and then wiggle the block back and forth to orient the edges appropriately. Children show similar age-related improvements in pre-orienting rods to fit into slots.

However, in some cases, infants (like adults) show evidence of their intentions for the second step in the sequence as they are performing the first step (Claxton, Keen, & McCarty, 2003). Infants place a block atop a block tower more slowly than they chuck a block into a bin. But remarkably, when the block's destination is the tower, the initial reach for the block is also slower than when the block's destination is the bin (Chen, Keen, Rosander, & von Hofsten, 2010; Claxton et al., 2003). This intention-influenced initial action is not well explained by Gibson's proposals for visually controlled manipulation.

Some actions stretch so far into the future that information about the end goal is not immediately available to perception. For example, in tasks involving "end-state comfort," observers must alter the form of their initial action to take the end goal into account (for a review, see Wunsch, Henning, Aschersleben, & Weigelt, 2013). When flipping an upside-down glass to fill it with water, adults initially grip the glass with their thumb pointing down—an atypical grip—so that after flipping it, the thumb points up in a position comfortable for filling the glass. In contrast, young children flip the water glass with an initial thumb-up grip and end in an awkward thumb-down position. Similarly, when grasping tools such as spoons or hammers, infants and preschoolers always use a typical overhand grip. But when the handle points away from the dominant hand, an initial overhand grip leaves the hand in an awkward position for eating or hammering (Comalli, Keen, Abraham, Foo, Lee, & Adolph, 2016; McCarty, Clifton, & Collard, 1999). More generally, children do not show adult-like planning for end-state comfort for most tasks—turning handles, rotating dowels, and so on—until 9–12 years of age. Because Gibson's theory relies on perceptual information that is immediately available, he does not address planning for end-state comfort.

Conclusion: Learning to Learn

Perceptual-motor learning permeates Gibson's *Ecological Approach*. In Gibson's view, animals need not learn to associate perceptual information about the world with appropriate actions. He argues that association learning is not the primary mechanism for perception of affordances for locomotion, manipulation, or any other action. Indeed, forming associations would be maladaptive because affordances depend on *relations* between body and environment, not *fixed facts* about the body or environment. Simple association learning cannot work because the status of the body and the environment are always changing. Instead, animals learn to detect information for affordances in real time in their moment-by-moment, situation-by-situation interactions with the world. Thus, perceptual-motor learning involves learning to perform and hone exploratory movements that generate information for affordances, and learning to differentiate and use the specifying information to plan and guide actions adaptively—a process of learning to learn.

Given Gibson's emphasis on affordances, the exclusion of development from *The Ecological Approach* is a serious omission. Development alters affordances. Developmental changes in the body (e.g., the ability to walk) and the environment (e.g., the new vistas engendered by an upright posture) change the available perceptual information and enable new opportunities for action. Moreover, development ensures learning to learn. Rapid body growth and dramatic changes in motor skills during infancy and early childhood discourage reliance on simple associations or fixed facts about the body or environment. Yesterday's body is different from today's body. A poor crawler last week is a more proficient crawler a week later. Solutions that worked earlier in development may not hold at later points in development. Thus, infants and young children are forced to learn in the midst of rapid and dramatic development change. The flux of development creates exactly the type of flexible and adaptive perceptual-motor learning that Gibson proposed.

Acknowledgments

Work on this chapter was supported by the National Institute of Child Health and Human Development (R01-HD033486 and R01-HD086034) to Karen Adolph. We are grateful to Jennifer Rachwani and members of the NYU infant action lab for their insightful comments.