

Going Somewhere: An Ecological and Experimental Approach to Development of Mobility

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This article formulates a framework for understanding mobility and how it develops. Research is summarized as a foundation for a theoretical framework. Studies are briefly described that deal with development of detection of a surface of support adequate for traversal, development of the ability to maintain equilibrium during stance and bipedal locomotion, and development of guided locomotion on a path to a destination in a cluttered environment. The informational basis for perceiving essential behavioral supports is examined. The concept of affordance as it relates to and is constrained by developing exploratory and action systems is stressed as an essential part of the theoretical framework for development. Mobility development is seen as best approached within a functional systems theory with components, both perceptual and motor, coming together in the course of development to permit emergence of new skills, such as crawling and walking, in the service of going somewhere.

THE CONCEPT OF MOBILITY

A brief glance at recent conference proceedings and symposia tells us that concern with action is in the air, after many years of neglect by psychologists. Perception and action, action and cognition, neural programs for action, and physical models for action systems are only a few ways action is being addressed. Old questions, such as "Does perception guide action?" or "Does action follow on decisions made by an executive (presumably cognitive) system?," are being reexamined. Mobility rates high among the topics of interest, and it stands out as having a new look of its own. The concept is a broader one than action, certainly not referring to isolated movements or even to semi-independent

action systems, but to a whole animal functioning in an environment that constrains its actions while offering the needed supports for action. The properties of the animal and the properties of the environment are joint determiners of any example of mobility that concerns a psychologist. Mobility implies action but also implies a place and an animal moving within that place and to other places.

Mobility has been of central concern for research on the blind. Emerson Foulke, a psychologist who chairs a group working for the National Research Council on electronic travel aides for the vision-impaired, remarked in a recent report: "We're used to miracles being accomplished by electronics, but we can't at present build really successful travel aides because we don't know what they are supposed to do. We simply don't understand mobility well enough" (National Research Council News Report, Nov. 1986).

A second applied area of concern has been addressed by clinical psychologists and neurologists: how to understand and help "clumsy" children. A fair-sized literature on this problem area exists, and attention has been directed not only to motor symptoms of clumsiness, but particularly to perceptual deficits (e.g., Dare & Gordon, 1970; Hulme, Smart, & Moran, 1982; Smyth & Glencross, 1986). One gets the feeling in glancing over this literature that consideration given the problem so far has been superficial and "test" oriented, and progress awaits understanding of mobility development in the normal child.

Recently, development of mobility in young children, especially infants making their first independent trips around the world, has become a concern for investigation. What are they learning to do or to understand? Is it really learning? What kind of learning? Does perception of the layout and its properties guide a beginner's attempts at locomotion? In what ways? What does the beginner know about the layout and what it affords? Does the beginner know where to go? How is such knowledge acquired?

These questions are important because mobility can be crucial for adaptive behavior in the world. The advantages of a mobile organism over a sessile one are obvious; we even think that a change to mobility in evolution may be associated with a change (a gain?) in intelligence. Mobility has two broad functions in adaptive behavior: executive—getting an animal from one place to another (to serve such ends as securing prey or eluding predators, reaching places of rest or safety, etc.) and exploratory or information-gathering (e.g., in foraging, seeking mates, or places of haven). This function—discovering sources of needed environmental support and paths to them—is as vital as the executive function.

Vision is unquestionably of prime use in locating environmental resources. The blind child is typically slow to explore the world and seek out goals (Fraiberg, 1977), resulting in a delay in motor and cognitive development. A study by Adelson and Fraiberg (cited in Fraiberg, 1977) found that:

blindness has relatively little impact upon postural achievements in the otherwise normal and well-stimulated blind infant. However, blindness is associated with a marked delay in the achievement of mobility skills. We would argue from this that vision must play a more central role in the achievement of mobility and locomotion than it does in the establishment of stable postures. (pp. 207-208)

Fraiberg goes on to say:

In the last trimester of the first year most of the blind children in our group had reached out into space with their hands for something they heard and wished to hold. Thus they indicated an awareness of a solid, graspable object "out there." Once this reach on sound was achieved mobility soon followed. And as each child began to raise himself into a sit and up to a stand and to creep across the floor he mapped the space around him as he went and began to furnish the void, slowly. When he stood up he came upon things from a new angle and needed to remap his entire space once again. He could not do this with one sweeping glance as the sighted child can. He had to do it painstakingly at first, one step at a time so to speak, feeling his way repeatedly as he gained familiarity with his old world in a new position. (Fraiberg, 1977, p. 218)

So blind children achieve mobility, but they must, it would seem, do it a hard way. Inability to detect visually interesting goals at a distance, to follow a path visually to a sounding object of interest, to examine visually the surface of support for evidence of traversability, and unavailability of optic flow patterns useful for monitoring one's position relative to the layout and maintaining equilibrium during locomotion, may all be responsible for a blind child's developmental delay. But, as yet, we know little more about development of mobility in sighted children than in blind ones.

Many years ago, the importance of vision for locomotion was described by J. J. Gibson and Crooks (1938):

Locomotion is guided chiefly by vision, and this guidance is in terms of a "path" within the visual field of the individual such that obstacles are avoided and the destination ultimately reached. These concepts of *terrain*, *destination*, *obstacle*, *collision* and *path* should be applicable to any type of locomotion, whether that of the infant learning to walk, the open field runner in football . . . or the operator of an automobile. (p. 454)

In the past few years, these concepts have been subjected to examination in children learning to walk. This article reviews some research on the development of mobility and considers its implications, seeking a theoretical framework for understanding mobility and its development.

First, we consider briefly some specific functions of vision in locomotion that

underlie our research program. Three distinct functions stand out. Most obvious is its function of *guidance to a destination*, involving avoidance of obstacles, steering and staying "on course," and monitoring speed in relation to obstacles and straight-aways. Everyone would concede that pinpointing a target, aiming at it, steering toward it, avoiding obstacles on the way, selecting the most economical route, slowing down at turns, and not colliding with the goal on arrival are critical skills for all methods of locomotion, from crawling to flying a plane. Prescriptions for visual control of locomotion were given by J. J. Gibson (1986/1979, p. 227, p. 232 ff).

In formulating a set of rules for traveling to a destination, J. J. Gibson made use of his concept of *affordance*—the utility of environmental supports, such as surfaces, objects, and co-occurring events for actions to be undertaken. For example, an object in the traveler's path affords detouring, whereas an opening affords moving through it. Affordances must be specified by information available to the traveler. To describe this information, Gibson's rules were stated in terms of *flow patterns in the optic array*. When the animal is moving, the information for vision is constantly changing and must be described as flowing, not static. For example, the direction of locomotion is specified by the focus or center of outflow; loss of structure outside a closed contour during approach specifies an obstacle; gain of structure inside a closed contour specifies an opening. As Lee (1980) said, "The fundamental ecological stimulus for vision is not a camera-like time-frozen image but a constantly changing optic array or flow field, the description of which must be in spatio-temporal terms" (p. 169). The indications are that even very young individuals are able to detect this kind of information. Studies of steering a course to a goal by an ambulant infant are as yet practically nonexistent, but experiments with "looming" stimuli suggest that there are precoordinated systems for responding appropriately to flow fields before an infant is mobile, a kind of "pre-view of adult function," to borrow a phrase of Trevarthen's (1982).

A second way in which vision is important in the control of locomotion is in detecting information specifying traversability of the terrain. Does the surface ahead have the requisite properties for affording traversability? Surfaces may or may not be of a kind to support a moving creature the size of even a 9-month-old crawler or a novice walker. At the very least, they must be horizontal, flat, firm, and of appreciable extent. The myriad variations possible in a potential surface of support are suggested by the large vocabulary available for describing them: They may be bumpy, bouncy, compliant, coarse-grained, deformable, dry, dusty, dented, frictional or frictionless, flat, firm, greasy, grainy, hard, horizontal, inclined, jiggly, moving, resistant oily, opaque, pliant, perforated, rough, rigid, rutted, resilient, stable, slippery, sticky, smooth, soft, swampy, sloping, solid, shaky, steep, transparent, uneven, viscous, vertical, wet, wobbly—and this is only a partial inventory.

All of these terms refer to the affordance of a surface for a creature on the

verge of embarking on it. Visual perception presumably furnishes guidance for movement onto the surface or avoidance of it and, perhaps, the mode of movement safest to undertake. There is often information specifying most of these properties in the optic array, thus permitting early warning of potential disaster. But other information is available through haptic exploration—important (especially to the blind traveler) but limited in some respects, for example, in perceiving extent and clutter ahead. A third source of information could be events occurring on the surface in the perceiver's presence. A car ahead skidding on an icy road or sinking in sand or snow is a potent source of information for an adult driver. Sounds accompanying the event may be informative, and blind pedestrians apparently do sometimes use them.

The third role of vision in locomotion is less obvious, but equally essential. Flow patterns in the optic array are a critical source of information for maintenance of postural stability in bipedal locomotion. Maintaining an upright posture is not a matter of passive quiescence, but is an active process of compensating for loss of balance (Stoffregen & Riccio, 1988). Somesthetic, vestibular, and visual systems all contribute information for the control of this process; the visual system is most prominent. As the body wavers forward or backward, flow of the total optic array results, signaling a compensatory action in proportion to the magnitude of the flow. In experiments with a "swinging room," Lee and Lishman (1975) showed that simulated flow resulting from a stagger or slight loss of balance not only specifies loss of balance but controls action that compensates for it. As an animal changes position even slightly, not only in walking or running, it is not surrounded by a fixed "picture" to look at but, instead, is creating a continuous change—a flow of the entire optic array. The flow itself is structured by features of the layout as well as by the mover's type of action, path, and speed of movement.

Is flow of structure of the optic array already useful to the human infant as mobility begins, or must the infant learn as he or she practices self-initiated locomotion to use it for stability and guidance? Research directly addressing this question is recent, but there are a few well-established relevant facts. Studies of infants' responses to "looming" objects and shadows began in 1970. Very young infants (2 months or less) were shown to make avoidance responses to accelerated magnification of an object or shadow (Ball & Tronick, 1971; Bower, Broughton, & Moore, 1970). The avoidance behavior did not occur if the shadow or object was not on a collision course nor when it retreated rather than approached. This is a nice case of perceiving an affordance at a very early age; the accelerating magnification of an opaque contour in the array specifies approach of an obstacle, and it affords avoiding, ducking, and getting out of the way. The case is not one of flow patterns produced by self-movement, but of optical flow induced in part of the array by movement of an object in the layout—a different case, but nevertheless one that demonstrates ability shortly after birth to respond to invariant information over time.

The conclusion that the infant's avoidance activity is a true case of perceiving the environmental affordance of an object on a collision course is strongly supported by an experiment of Carroll and E. J. Gibson (1981), in which the approaching contour was presented to infant subjects as an obstacle, on the one hand, or an aperture on the other. The obstacle (an opaque screen) progressively covered the background layout as it approached the infant (note J. J. Gibson's rule that loss of structure outside a closed contour during approach specifies an obstacle); in contrast, the aperture, an opening the size of the obstacle, uncovered more and more background as it approached (gain of structure inside a closed contour during approach specifies an opening). It could be compared to the effect produced by a person moving toward an open doorway that affords passage through, as opposed to a blockade, a situation that has been studied recently with older subjects¹ (Warren & Whang, 1987). The affordance is obviously different for an obstruction than for a passage; infants discriminate them, showing avoidance behavior only to an approaching obstacle.

Although this example provides evidence for differentiation of affordances specified by varying arrays incorporating optic flow, it is not direct evidence for use of flow information provided by self-movement. Lee and Aronson (1974) found evidence that newly walking infants were strongly influenced by optic flow in maintaining upright posture. We carry their findings further in our research and suggest that although sensitivity to information in optic flow is already present in the neonate, there is further development via perceptual learning—differentiation of flow fields in relation to finely tuned perception of affordances.

The rest of this article summarizes research performed in our laboratory on all three of these functions of perception in guiding action. The research serves as a foundation for theoretical concepts that help in understanding mobility and how it develops. We begin with traversability of surfaces, because that is where our research began, and finish with some research on guidance around obstacles to a destination, the most comprehensive of the three functions.

RESEARCH ON TRAVERSABILITY OF SURFACES

The affordance of a surface for supporting a moving creature is a major consideration for mobility, depending on external environmental properties of the surface and, at the same time, on the structure and capacities of a particular animal. The surface of a pond may afford support for a water bug, but it will certainly not for a walking person or even a crawling baby. A jogger monitors

¹See Palmer, C. (1986, April). *Between a rock and a hard place: Babies in tight spaces*. Poster presented at SRCD, Baltimore, MD.

the surface ahead with care, noting potholes or tree roots when the path is not clear and adjusting pace and course to avoid them. The driver of a vehicle is equally watchful, having no wish to skid on a patch of ice, to get stuck in the mud, or to break a spring. What about a newly mobile child faced with a novel surface? Has this child's experience with rolling and rocking to and fro on a surface of support prepared him or her for self-initiated safe traversal? So far as we know, the only earlier relevant research was the work with the visual cliff (E. J. Gibson & Walk, 1960; Walk & E. J. Gibson, 1961). Babies capable of crawling hesitate to cross a transparent surface placed 4 ft above the floor, even though a parent on the other side urges them to come.

Does the baby's refusal to set out on the transparent surface indicate an innate fear of heights or falling? Probably not—it seems more likely that such fears are acquired later (Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978). It is more reasonable to suppose that the baby, inspecting the layout, detects no visible information for a surface of support extending outward toward the parent. In fact, there is no visible surface to crawl on. If the baby engages in haptic exploration, a firm substance can be detected, but it conflicts with what can be seen. With the aim of investigating what a baby knows or seeks to find out about surfaces of support in the interest of going somewhere, we undertook a number of experiments with crawling and newly walking infants, comparing surfaces varying in their affordance for traversal and in the information presented by them (E. J. Gibson et al., 1987).

Rigid Versus Deformable Surfaces

The property chosen for beginning our investigation was a surface's relative rigidity or deformability. The plan was to put young ambulatory infants in a situation where surfaces varying in an important property of traversability stretched between the infant and an objective (a parent to be reached). We observed spontaneous behavior before embarking on a trip over the surface, such as exploring the surface, avoidant or playful activity, latency to embark, and mode of locomotion. The subjects were both walkers and crawlers, because an affordance varies with capacities of the animal and surfaces may differ in their affordances for walking as compared with crawling.

The basic experiment presented the baby with a "walkway" on which interchangeable surfaces could be placed (E. J. Gibson et al., 1987). The baby was placed by a parent on a starting platform at one end, and the parent then moved to the other end facing the baby. The starting platform, covered with burlap, was always the same. The baby was placed in a sitting position. The parent was instructed to smile at the baby, but to say nothing for 30 sec. If the baby did not move off the starting platform by that time, the parent urged the baby to come, and finally produced a bunch of keys as an enticement. A trial lasted 2 min and was videotaped for later detailed coding. Each subject was presented with two

surfaces, one at a time. One was the rigid surface, constructed of firm plywood and covered with a tautly stretched white fabric crosshatched with a pattern of brown diagonal lines. The surface looked hard to an adult and felt hard to the touch. The other surface was constructed of a waterbed, covered with the same fabric. The waterbed was gently agitated, revealing its deformability visually. It was also deformable to the touch. Thus, both optic and haptic information specified the contrasting affordances.

The videotapes were coded for latency to embark on a surface, amount of time spent in visual and in haptic exploration, and amount of time spent in "displacement" behavior (looking away from the parent and the intervening stretch of surface, playing with safety nets, opening the curtains behind the starting platform, etc.). Taken together, these measures showed that the rigid surface was embarked on sooner, explored less, and gave rise to less evasive or playful activity than the deformable waterbed surface. But in comparing the crawling with the walking infants, the difference was attributable to the walkers alone. Crawling infants showed as little hesitation in crawling off on the waterbed as on the rigid surface, and as little displacement behavior. Both groups explored the surfaces visually and haptically, but walkers explored the waterbed longer. It was notable, too, that although some of the walkers crossed the rigid surface on two feet, getting up and walking to the parent, none attempted to walk on the waterbed—all crossed it crawling. These results were confirmed in another experiment with a choice method (presenting both surfaces at once, requiring a choice of route to the parent). It seemed that presentation of novel surfaces did induce some exploratory testing of surface properties by both crawlers and walkers, but walkers discovered the nonaffordance of the waterbed surface for maintaining an upright position and walking over it.

Visually Impoverished Surfaces

It might be that walkers, about 3 months older than crawlers, are simply more wary of any new surface. Experiments were undertaken, following the same methods, except the previous rigid surface (covered with a strongly textured pattern) was compared with a plywood surface covered with black velvet (E. J. Gibson et al., 1987). In this case, the surfaces were equally rigid and bipedal locomotion was equally possible, but the black velvet surface presented very poor optical information to specify its surface properties. In this experiment, both groups of infants hesitated far longer to embark on the black velvet surface and both spent significantly more time in displacement activities. There was no difference in time spent in exploration of the surfaces in either group. Both crawlers and walkers were wary of the black velvet surface and seemed uncomfortable with it. In a choice experiment, very few chose it for crossing. But the walker-crawler distinction did not occur. Furthermore, the walkers were no

more wary of walking on the black velvet surface (when they did cross it) than of the textured one; in fact, equal numbers got up and walked. These findings confirmed our conclusion that the walkers, with a new-found ambulatory competence, were seeking information for an affordance not yet relevant for babies still in the crawling phase and acting on it. Crawling babies were equally wary of the visually impoverished surface. No distinction appeared, because the affordance was the same for walkers; the surface was repellent, but walking was as possible as crawling.

Use of Haptic Information

The information actually used by the walkers in this highly adaptive differentiation of the rigid and the deformable surface is a matter of great interest. Most of the infants capable of walking actively palpated the deformable surface with their hands and occasionally bent forward and pushed it with both arms. But, did they actually use the haptic specification of deformability in detecting that the surface did not afford standing and moving forward on two legs? This source of information would be available to blind infants (although it might only be triggered by visually detecting information specifying a nonrigid surface). The question led us to an experiment in which both the rigid and deformable surfaces were presented covered with transparent plexiglass (E. J. Gibson et al., 1987). The waterbed was agitated, so as to present visible "waves." Walking infants were then presented with each of the surfaces as in earlier experiments. The results were quite clear. There was no longer a significant difference between the two surfaces. Furthermore, the same number of infants walked across the rigid and the waterbed surfaces when plexiglass covered them. Either the haptic information itself or the visible consequences of haptic exploration were effective for detecting the surfaces' affordance for walking.

Partially Transparent Surfaces

The reluctance of infants to move onto a visual cliff, where the rigidity of the surface is haptically detectable, contrasts with this finding (E. J. Gibson & Walk, 1960; Walk & E. J. Gibson, 1961). In that case, the conflicting information generally resulted in control by the lack of optical specification of a surface. Why is there a difference between the two situations? In the case of the underlying waterbed, an opaque surface is detectable, along with haptic rigidity. Information for some kind of surface may be important. We performed another experiment (E. J. Gibson, 1984) relevant to this question. In this case, both crawlers and walkers took part. The rigid surface used in previous experiments was again used as a comparison standard surface, and the experimental surface was a net stretched under plexiglass. The net made a pattern similar to the brown and white diagonal pattern of the standard surface, but the floor, 4 ft

below and well-lighted, could be seen clearly through the holes. Results in this experiment were similar for crawlers and walkers. All the infants hesitated markedly to embark on the net/plexiglass surface, but a majority did eventually cross it to the parent within the 2-min time limit. As many walkers walked upright over this surface as did over the opaque rigid surface. Three walkers and two crawlers out of 16 in each group refused to cross, whereas all crossed on the rigid surface. Seeing the floor below was definitely a deterrent, and latencies to cross were long. Older infants in a few cases shook their heads as parents urged them to come and pointed to the floor below, but optic specification of some kind of surface was sufficient to differentiate this surface from the cliff (clear plexiglass) surface. Visible texture is evidently an essential component of optic information for a surface of support.

Surfaces Specified by Events

When experiments with the visual cliff or ambiguous surfaces (e.g., the black velvet or the net surface) were described to an audience, it was often suggested that an event of some sort taking place on the surface would provide evidence for an infant that the surface is really capable of support and give the infant confidence to proceed. The suggestion seemed reasonable enough that we undertook several experiments to test it. To give the best chance of success, we chose not to use the visual cliff, which might be too forbidding. Instead we used the net under plexiglass, which deterred the infants significantly but not totally. The experiment was set up with two groups: in one, the control group, all infants received two trials, one condition with the standard surface and the other with the net/plexiglass surface (no event); in the other, all infants received the standard surface and the net/plexiglass surface after witnessing two events taking place on that surface. We chose two events that captured the baby's attention—one was a hard ball bouncing on the surface and the other a stick (wielded by an experimenter) beating the surface. Both yielded optical and acoustical information specifying the surface's rigidity. The baby's parent held the child up at the opening over the starting platform so as to observe an experimenter producing the two events; the baby was then put on the platform as usual. Differences in latency, displacement, and exploratory behavior between the standard surface condition and the net surface condition were computed and the differences compared for the two groups. We had expected that observing the events would result in less hesitation, displacement, and exploration for infants in that group, and thus reduce the difference between standard and net conditions for them. The results did not confirm this expectation, however. The two groups did not differ significantly on any measure.

Perhaps the evidence given by external events for surface properties is too indirect and inferential for it to specify a firm surface to infants. Nevertheless, we thought that we could give a better chance for a difference to show up if we

contrasted two conditions, one in which events demonstrated a firm surface and the other in which the same events demonstrated a nonrigid, deforming surface. To implement such an experiment, we chose the black velvet surface. The contrasting conditions were (a) black velvet covering a firm rigid surface and (b) black velvet covering the waterbed. The waterbed was first presented unmoving, so that the events the infant witnessed were responsible for deforming and rippling the surface. Two groups of subjects were run. One group was given the black velvet rigid surface plus events and the standard textured firm surface; the other was given the black velvet waterbed surface plus events and the standard, textured firm surface. Both crawlers and walkers took part in each group. Without events, the two black velvet surfaces looked alike to observers when the babies were first shown them. The effect of the events might be to highlight the difference between them, reducing the ambiguity of the black velvet so as to make it more attractive when the surface was firm and less so when it was nonrigid. It was also possible to compare the black velvet rigid surface plus events with the black velvet rigid surface where no events had been presented (in an earlier experiment).

The results of this experiment, although interesting in several other respects, again failed to produce conclusive evidence that the events specified surface features to the infants, or if so, that they used the information to facilitate appropriate action. Walkers showed a slightly greater tendency to be influenced by the events, but not to a significant extent. We concluded that affordances for action, at these ages, are not as easily learned from witnessing events taking place on a surface as they are from directly exploring the surface visually and haptically. The available information may be detected, but not perceived as relevant for locomotor behavior or support of one's own body weight.

Perception of Surface Properties by Preambulatory Infants

So far, our experiments had to do with infants who could walk or crawl. A question as yet unanswered is: How early do infants attend to surfaces of support and detect properties such as rigidity, and supportability, if not traversability? The earliest age suggested for detection of supportability comes from evidence of placing responses with the arms extended toward a surface when an infant is lowered downward in its direction. Peiper (1963) noted that the placing response appeared at about 6 months. Careful research by Walters and Walk (1974) found the response to be present in all the crawlers they tested at 8½ months or later. It is possible that reaching, when lowered to a supportable surface, antedates crawling, emerging with skilled exploratory use of arms and hands. But it may be that supportability for traversal is not detected until action systems rendering the infant mobile have matured.

The past decade has turned up considerable evidence for precoordinated

systems that are a sort of "preview" of later functioning—functions "that will only really get into action at some later stage of development" (Trevarthen, 1982, p. 42). Such systems, perhaps genetically based, could prepare the animal for later differentiation and integration of behavior, including learning sophisticated affordances, within an appropriate ecological setting. Communication seems to incorporate precoordinated systems and functions of this sort, such as very early mother–infant interchange, attention to voices and faces, and imitation of facial expressions. Mobility seems to be a good candidate for this type of broad system. Infants might attend, at least in limited fashion, to surfaces of support and their properties, because such surfaces (e.g., the ground) always characterize the layout where human actions take place.

We sought to investigate this question with precrawling infants, necessarily adopting a method that did not require them to go anywhere. We chose habituation, the basic paradigm being habituation of the infant to videotaped displays of a surface on which an event was taking place, followed by a tape of an event on a different surface (one having different properties for support).² The two surfaces were a net (nonrigid) and a sheet of clear plastic overlaying the net, not itself visible (rigid). Only the occurrence of the event made these surfaces distinguishable.

The habituation method typically involves repeated presentation of some event until the level of attention drops significantly; after achieving the drop, a second event is presented. If there is renewed attention, the infant is assumed to have discriminated the events. Our first experiment contrasted precrawling with crawling infants, with looking time as the measure of attention. There was some evidence that both groups dishabituated to the changed surface, crawlers to a greater extent than precrawlers. The crawlers also showed greater dishabituation when the surface was changed to rigid from nonrigid than vice versa. It seemed possible that the crawlers were beginning to detect an affordance—the supportability or traversability of the firm surface—that the precrawlers did not detect.

Because the method of habituation, as such, can only provide evidence for discrimination of a difference and not detection of an affordance for action, we designed a new experiment that may yield evidence for our hypothesis: Detection of the affordance of a surface, given information specifying it, awaits emergence of the action system relevant for the affordance. Crawlers might detect the traversability of a surface, whereas precrawlers, although discriminating superficial features of the display (e.g., height of a ball bouncing on the surface) might not. The new experiment involved preferential looking at two videotaped events, presented side by side. The event was a hand extended and pushing rhythmically on each of the two surfaces used previously (the net or the plexiglass with the net stretched underneath it). As the infant watched the two

²These experiments will be described in detail elsewhere, and are summarized only briefly here.

taped events, its hands rested on a hidden surface in front of it—either firm rigid plexiglass or a net. Each subject observed the tapes for 90 sec with hands on the rigid surface and 90 sec with hands on the net. The prediction was that the subjects would look preferentially toward the event implicating the surface being felt at the time.³ In a first run of the experiment, we found that the crawlers did prefer watching the surface their hand was presently feeling, matching its substantial qualities, but the precrawlers did not. If this result is replicated in ongoing research, we think it is an indication that infants' readiness for appropriate action on a surface of support may constrain their perception of the affordance of relevant environmental properties. Haptic manual exploration of surfaces occurred frequently in our walkway experiments with crawlers and walkers and appeared to be used as information for traversability of a surface, so unified bimodal recognition of the surface's rigidity suggests ability to use the information for specification of its affordance.

RESEARCH WITH NOVICE WALKERS ON MAINTAINING A STABLE POSTURE

Maintenance of a stable posture by bipedal creatures is not a simple feat, but rather a very active process of responding to perceptual constraints that control it (Stoffregen & Riccio, 1988). It is performed so economically and unconsciously in young adult persons that it is generally just taken for granted. Loss of it in extraordinary circumstances, such as a lurching airplane or ship, is apt to be attributed to unusual perturbation of the vestibular system. Few people recognize that maintaining a steady stance is a skill requiring a long development to perfect: its achievement is an integration of systems involving not only vestibular but somatosensory and notably visual information. Shumway-Cook and Woollacott (1985) in an article on development of stability, set achievement of the adult form of postural control as late as 7 to 10 years. In the youngest group studied (15 to 31 months), they noted that visual-vestibular information primarily controls stance balance. As others have suggested, there is reason to think that vision is dominant during this period. Between the ages of 4 and 5 they found that "somatosensory inputs increase in importance in mediating postural responses, suggesting a shift away from visual dominance" (p. 146).

Work on adults establishes that information from the optic array still plays an important role in maintaining equilibrium despite the ontogenetically increased role of mechanical-somatic information. Lee and Lishman (1975) found that

³Experiments with bimodally specified visual-auditory events have shown that infants tend to prefer watching a unified event, one specified by both modes. Here, we predicted that haptic-visual concurrence of specification is preferred.

vision played an important role in controlling stance in adult subjects. Subjects standing in a "swinging room" swayed as the room moved in response to optic flow patterns produced by room movement, despite the fact that they were standing on a stable, nonmoving surface of support and underwent no somatic or vestibular disturbance. Lee and Aronson (1974) presented newly walking infants with flow patterns generated in the swinging room and found that they not only used optical flow to maintain a standing posture, but were dramatically susceptible to it, frequently falling down as the room was moved. Later studies (Butterworth & Hicks, 1977; Forssberg & Nashner, 1982) found that optic flow effects on maintenance of equilibrium were reduced at older ages, in harmony with the findings of increased somatosensory control by Shumway-Cook and Woollacott (1985).

Work by Stoffregen (1985) showed that control of stance by optical flow in adult humans was effected principally by flow structure characteristic of the periphery of a display, rather than by its central radial outflow. In light of the developmental change between 1 and 10 years in the relative dominance of optical flow over somatosensory and vestibular control, it is possible that shift in utilization of information for postural status might involve differentiation and refinement of perception through detection of different specifications in optical flow patterns. Structural aspects of flow can specify different affordances for different actions involved in mobility. For example, optical flow structure specifying an obstacle is different from that specifying an opening. The focus of radial flow specifies direction of locomotion for one moving toward it, whereas perturbation of flow at edges of the surrounding layout does not, but nevertheless specifies a fall or loss of support. Perceptual learning during early practice of walking might lead the young walker to new integrations of optical information and action as more specific affordances are learned for postural control and steering.

Experiments were undertaken by Stoffregen, Schmuckler, and E. J. Gibson (1987) to investigate the effects of optical flow when it was restricted to either the central or the peripheral parts of the visible optic array presented to young walkers. We were interested in the effects of optical flow on both stance and walking (the latter hitherto not investigated). A room similar to that used by Lee and Aronson (1974) was constructed so it moved back and forth on rollers. It was closed on three sides and open on the fourth. Standing, immobile panels covering a side could be erected so that visible room movement would be confined to only the uncovered wall or walls. Thus, optic flow, as the room was moved backward or forward, could be made available in the frontal array alone or in the peripheral array alone when the subject faced the rear wall of the room. The subjects were children ranging in age from 1 to 5 years, a period that covers the time of shift toward decrease in visual dominance (as noted by Shumway-Cook & Woollacott, 1985). Walking experience ranged from 2 weeks to 4 years. Restricted flow in the central or peripheral areas was compared with global flow

when all three walls were uncovered during room movement. The child's parent was seated on the floor at the center rear wall of the room to attract the child's attention in that direction. With the younger children, observations were made when the child was standing still and during locomotion toward the parent. Videotapes of the complete experiment were coded by two observers to compute sways and falls.

Both swaying and falling occurred during room movement. Falls were confined to the younger children, who were most affected by room movement in accordance with all previous findings; children who have only recently developed an upright posture are highly dependent on information in optic flow for maintenance of postural stability. The location of flow in the peripheral optic array proved more effective in producing compensatory response than the frontal array, replicating overall the earlier finding of Stoffregen (1985) with adults. Peripheral flow was almost as effective as full room flow, but compensatory response was greatly reduced when central frontal flow alone was available. However, we observed an age difference in susceptibility to frontal flow. When the subjects were divided into two groups, those under 2 years ($n = 30$; M age = 15.77 months) and those between 2 and 5 years ($n = 24$; M age = 3.4 years), the older group showed no readily observable reaction to frontal flow, whereas the younger group was still significantly affected. Thus, infants still in the process of acquiring stable, upright posture are not only more susceptible to flow information for loss of balance, but they also have not yet differentiated completely the central radial as contrasted with the peripheral optic flow.

Why should this structural aspect of flow be differentiated at all? One reason may be that central radial flow is of prime utility for steering around obstacles and keeping on course during locomotion. Economical use of information in the array might be optimized by attention to such information for steering, whereas peripheral flow of smaller magnitudes, specifying staggers or wavering, would be left to control postural adjustments for staying upright. This fine tuning of perceptual control might be learned mainly during the actual practice of locomotion while "going somewhere." The age difference we observed is consistent with such a course of development. If practice in walking is important in bringing about the central-peripheral distinction observed in older subjects during room movement, the movement should produce disturbances such as staggering during walking as well as standing still, especially in very immature walkers. We found that our youngest subjects (the group under 2 years) were indeed as susceptible to room movement during walking as when they were still. The difference between peripheral and central flow was present, but there was a significant effect of central flow on compensatory actions. These findings led us to construct a longer space, described in the next section and referred to as the "moving hallway." We hoped to investigate walking when steering required particular attention, observing postural disturbances when the child was actually going somewhere.

THE EFFECT OF IMPOSED OPTICAL FLOW ON GUIDED LOCOMOTION

We come now to the third function of vision in locomotion—its role in guidance to a destination. This role is the most prominent of the three we have studied; yet research on how skill in achieving it develops in rare, despite considerable interest in orientation and way-finding in older children (Hazen, Lockman, & Pick, 1978; Pick & Lockman, 1981).

One of our experiments on the walkway is indirectly related to the problem of guidance to a destination while monitoring the terrain to be traversed. We called the study the “hole-patch” experiment, because it originated in a discussion of the Gestalt contention that the ground behind a “figure” is perceived as extending continuously behind the figure that appears to cover it. A 46 × 46 cm square of brown wallboard (the “patch”) was placed on the textured surface of the walkway, which served as our customary rigid control surface, about halfway between the starting platform and the waiting parent. For a contrasting condition, the surface of the walkway was a large sheet of plexiglass covered with brown wallboard, with a hole cut out where the patch had been placed. Sixteen crawlers and 16 walkers participated in the experiment. The prediction was that they would go over the patch, but detour around the hole. The majority of the subjects did go over the patch (100% of the walkers and 78% of the crawlers). As for the hole, 11 of the walkers detoured around it, whereas only 3 of the crawlers did. It appeared that the walkers differentiated the two surfaces better than the crawlers, scrutinizing the terrain more attentively for pitfalls and steering around them in the course of traveling to a destination. As for the Gestalt question, the answer is positive; even most of the crawlers treated the surface as extending under the occluder. Because terrains are often uneven, presenting inclinations, steps, holes, bumps, as well as larger obstacles, attention to the path may be critical, even when the goal is in sight.

Other research with children under 18 months has centered on egocentric orientation as opposed to orientation to the objective layout; beyond this age, emphasis has usually been placed on development of “representation” and ability to find a route to a destination that is hidden or, at least, not presently in view (e.g., Rieser & Heiman, 1982). Neither of these questions is our major concern; we are asking how a young walker guides locomotion (steers) and maintains balance when the target destination is within view, but in a more or less cluttered layout.⁴

A few researchers have come close to our problem in studies of early detour

⁴Anyone who thinks there is no problem here should watch a young toddler find his way around furniture to an attractive toy, staggering and occasionally bumping into something but getting there, or even riding a tricycle around the house (God forbid) to some destination. In the latter case, different postural synergies require control, but steering is a real task.

behavior. Lockman (1984) investigated both reaching and locomotor behavior in infants of crawling age when an attractive object was placed behind a barrier as the infant watched. Typically, the infants were successful at the reaching task (M age = 9.7 months) before the crawling task (M age = 11.2 months), although all were crawling before the experiment began. Performances were compared when the barrier was opaque and when it was constructed of transparent plexiglass. Infants reached around a plexiglass barrier about a month later than they reached around an opaque one. There was a tendency for a crawler to detour later round a plexiglass barrier than an opaque wooden one, but with a shorter developmental delay than that observed for reaching. Because a truly transparent barrier could present no optical information for a surface (like the surface of a visual cliff), this does not seem surprising. Whether the infants explored the barrier haptically in both cases is not clear; but in the case of the plexiglass, some infants tried to reach through it and thus must have obtained some haptic information when reaching. Perhaps use of the affordance thus specified ("go around this object") was made relatively earlier, compared to the opaque barrier, in the locomotor task than in the reaching one because the babies were older and more mature with respect to the utility of haptic information unaccompanied by optical information specifying the same affordance. Differentiation of modal information is probably going on about this time (Walker-Andrews & E. J. Gibson, 1986).

A study of detour behavior by McKenzie and Bigelow (1986) blocked one path to a goal (itself visible) and left one open to find out whether ambulatory infants could choose the shortest route and also show flexible behavior when the barrier was moved. Subjects were 10, 12, and 14 months old. After they were shown in aerial view, the subjects were placed in front of a barrier open to allow passage at one end. The infant's mother stood behind the barrier, displayed a toy, and then sat down. She was not visible as the infant sought a route to her. Nevertheless, even the 10-month-old infants went around the barrier and reached the goal. However, when the position of the barrier was shifted to the opposite side after four trials, several of the 10- to 12-month-old infants persisted in choosing the earlier route. At 14 months, all the infants changed routes successfully and generally followed a shorter, more efficient route. None of the children in the youngest (10 month) group were walking, but almost all of those in the 14-month-old group were. Perhaps the older ones had a better view of the layout, because being upright and above the floor gives a better perspective. Transparent barriers as well as opaque barriers were presented to the infants. The efficiency of the route chosen did not, in this experiment, vary with transparency of the screen.

None of this research (nor any other we have found) deals directly with the problem of steering and monitoring posture—presumably, a simpler problem than learning to find the way around a barrier when the consequences of taking alternative routes are not directly specified. But we see the importance of its role

in the handicaps of the blind child, who may be quite as quick at learning, remembering, and making inferences as the seeing child, but who has to get the basic knowledge for these more cognitive performances indirectly. We suspect that learning goes on even in the presumably easier task of sighted children as they first guide themselves toward visible goals, acquire skill in their new motor capacities, and get together the act of walking, staying upright, and moving around a cluttered environment.

If there are two distinct functions for vision in walking, as we suggested in the previous section, one to maintain postural equilibrium and the other to guide the walker's path in relation to obstacles, openings, and a target destination, we can make some predictions for development when the child tries to go somewhere in a cluttered place. We would expect improved postural control with walking experience if, as we have been urging, walking is a skill that improves as perceptual constraints and action become integrated and refined with practice and differentiation of structural aspects of optic flow; we would expect greater perturbation of equilibrium when the young walker's path wends through a cluttered place; and we would expect clutter as contrasted with a clear path to affect equilibrium during locomotion, but not when the walker stands still in the same place.

An experiment was designed to test these predictions by Schmuckler and Gibson.⁵ Overall strategy of the experiment was to test young children of different degrees of walking experience in a "moving hallway." These children walked through either a cluttered or an open area to a parent, with optical flow imposed at intervals, by moving the walls of the hallway around them. Stagers and falls were coded as the children walked and as they stood still in the hallway.

The hallway was constructed to move on bicycle wheels and offered a longer path to a destination than the moving room used previously (measurements were 12 ft long \times 3 ft wide). An experimenter was stationed at the open end, and a parent sat at the other. The subjects walked back and forth from one to the other, playing a simple game. Trials with room movement could be compared with trials without room movement. There were two conditions, one in which obstacles (orange traffic pylons) were placed in two positions in the hallway, so they had to be detoured around, and one without obstacles. In both conditions, subjects were observed walking and standing and with and without room movement. It was predicted that the obstacles condition, which called for complex steering to get to the parent, would generate more postural perturbation than the uncluttered condition when the hallway was moving, but only during active locomotion (when subject was walking, but not when standing still).

⁵See Schmuckler, M. A., & Gibson, E. J. (1987, August). *The effect of imposed optical flow on guided locomotion in young walkers*. Poster presented at the International Conference on Event Perception, Trieste, Italy.

Three groups of children with different lengths of walking experience took part in this experiment. The youngest group had a mean age of 15.4 months and mean walking experience of 2.7 months; the intermediate group had a mean age of 20.1 months and walking experience of 8.4 months; the oldest had a mean age of 29.5 months and a walking experience of 17.8 months. All subjects took part in both conditions of the experiment.

Results of this experiment were as predicted. Room movement resulted in significantly greater postural perturbation (staggered and falls) when the path was cluttered, but the effect was produced, as predicted, only during locomotion. Months of walking experience made a difference. In general, the older the child, the fewer staggers and falls occurred under room movement. All three groups showed a difference in postural perturbation during room movement when obstacles were present, as compared with no obstacles, and the child was walking. But the difference was relatively greatest for the youngest group and least for the oldest. The correlation of individual difference scores between this difference score and walking experience was significant, bearing out mean age differences.

An analysis of locomotion as a task, we think, requires a broad "systems" view (Thelen, 1986; Thelen, Kelso, & Fogel, 1987). Within this view, the results of the "obstacle" experiment just described suggest that the subtasks of maintaining stable posture while maintaining appropriate orientation to a seen goal develop in skill partly by differentiating information in an optic array that best specifies the two affordances, and that use of more specific information for the subtasks is maximized gradually for efficient performance. This change entails a kind of perceptual learning that has been characterized as "optimization of attention" (E. J. Gibson, 1969). In the final section, we fill in the concept of mobility development by suggesting a theoretical framework for approaching it.

THEORETICAL CONSIDERATIONS FOR MOBILITY DEVELOPMENT

There has been a movement in recent years to consider development of a complex activity, such as walking, in terms of systems theory (Thelen et al., 1987). Development of coordinated movement must be viewed as encompassing physical growth (e.g., anatomical changes) as well as behavior changes during ontogeny; that is, there is change both within the animal and in the relations between an animal and its surrounding environment. Change within the system has many components, which themselves exhibit change occurring at different rates. Development in an organized activity, such as locomotion, depends on the assemblage of the total system with all of its interlocking components. In Thelen et al.'s view, components of locomotor skill include pattern generation, articulator generation, postural control, sensitivity to visual flow, tonus control,

extensor strength, body constraints, and motivation. We sought to expand this list and, in particular, expand and attempt to analyze the role of perceptual systems in the total complex.

J. J. Gibson's (1986/1979) ecological approach to perception was placed within a functional systems theory framework. The perceptual systems (haptic, visual, somesthetic, etc.) are interdependent subsystems within the total functioning organism, concurrent with action. But the organism does not function in isolation; it is itself a subsystem in the animal-environment system: "Control lies in the animal-environment system. Control is by the animal in its world, the animal itself having sub-systems for perceiving the environment and concurrently for getting about in it and manipulating it" (J. J. Gibson, 1986/1979, p. 225). The key relationship between these subsystems is encompassed, for Gibson, in his concept of affordances. Information in ambient arrays of energy is available to the perceptual subsystems to specify what a given layout or event in the environment affords for actions such as grasping or walking.

Our research, placed within this broader context, is an attempt to investigate experimentally the development of affordances having to do with locomotion; in particular, the way visual and haptic systems come to utilize information in ambient optic and mechanical arrays for actively maintaining upright posture and for guiding actions such as walking to a destination. Because we are concerned with perceptual development, we have dealt with the way sub-functions involved in locomotion (stabilizing posture, selecting appropriate terrain, steering through a cluttered environment) make use of information in a structured array.

What have we learned from the research just summarized that might aid conceptually in understanding mobility development? We have learned that information utilized by a perceptual system, such as the visual system, may be differentiated with practice in locomotion, in order to optimize selection of structured information in the optic array for different aspects of a task like going somewhere. Differentiation of modal systems, such as visual, haptic, and somaesthetic occurs also, with improvement in skills, such as maintaining balance, by more economical assignment of control to haptic and somaesthetic subsystems, and perhaps less reliance on the visual system. Detecting the affordance of a terrain for such a task as walking also profits by differentiation of modal information for control, with increasing utilization of *haptic* information along with visual. *Exploratory* skills are used by infants as early as 8 months of age to detect affordances of a terrain confronting them if there is motivation that requires going somewhere. Exploratory skills increase as the infant's motor capacities mature and change in accordance with a shift in the task (e.g., to walking as opposed to reliance on only the earlier form of locomotion, crawling). But crawling can still be selected as a more adaptive form of locomotion when exploration has revealed evidence of nontraversability of a surface for walking

upright. Behavior control of this sort, we suggest, is the result of discovering an affordance.

Evidence has been uncovered suggesting that affordances are discovered in relation to maturation of new action systems, such as walking. Walkers heed the evidence for a compliant, deformable surface that provides poor support for maintaining upright posture and proceeding on two legs. They hesitate to embark on such a surface, and when they do, they do not walk. Prewalkers do attend to affordance of a surface for support, especially visual evidence for absence of a surface or impoverished visual evidence for a surface's properties. But we have evidence from recent experiments that whereas crawlers appear to detect information for the supportability of a surface—its substantial property—precrawlers may not. The precrawlers apparently detected visual evidence for some kind of difference in two surfaces varying in substantiality, but they did not unite this perception with haptic evidence of rigidity or nonrigidity, which together would provide information for the affordance of supportability. It seems that the property is best specified by an intermodal invariant which infants are more likely to detect after they have begun locomotion over surfaces—crawling to begin with—and learn to attend to properties relevant to such action.

Affordances, we suggest, are at least partially learned. The learning is primarily perceptual—differentiation of informative arrays, both modality-wise and within structure of a given array—and detection of supramodal information over modalities. In addition, there is learning through observation of the consequences of one's own exploratory activity. Maturation of other subsystems (e.g., action systems), as suggested in a systems analysis, is another factor in development of perception of affordances. These factors are closely interrelated in development. Weakness in any one—blindness or retardation in development of some motor ability, for example—will hinder overall development of a complex skill like walking, particularly when going somewhere.

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