The Self in Infancy: Theory and Research
P. Rochat (Editor)

CHAPTER 11

Self-knowledge of Body Position:

Integration of Perceptual and Action System Information

MARK A. SCHMUCKLER
University of Toronto, Scarborough College

There has been a recurrent fascination in psychology with describing and understanding the growth of self-knowledge in children. In general, this interest in the self has been widespread, covering a diverse array of ideas. For example, in her review of developmental perspectives on the self, Harter (1983) provides a partial list of the aspects of the self that have been studied by psychologists. In her words:

> [W]e encounter self-recognition, self-concept, self-image, self-theory, self-esteem, self-control, self-regulation, self-monitoring, self-evaluation, self-criticism, self-reward, self-perception, self-schematas, self-referent thought, self-consciousness, self-awareness, and self-actualization, to name the most prevalent exemplars (Harter, 1983, p. 276).

Related to such widespread interest, numerous theoretical proposals have been offered for understanding both the functioning of self as well as its development (see Harter, 1983, for a review). One recent theoretical formulation offered by Neisser (1988, 1991, 1993) undertakes a cognitive analysis of the self and its development by focusing on the different forms of information available to people. In Neisser's view, "... people have access to five basically different kinds of information about themselves. Each kind specifies a different aspect of the individual and thus implicitly defines a different sort of self" (Neisser, 1993, p. 3). The first of these selves, the "ecological self," concerns the relationship between the physical self and the physical environment, focusing on the individual as an active, causal agent in the world. According to Neisser, the information for this aspect of self is perceptual, with one directly perceiving one's self as acting within the world. Because the ecological self is based on perceptual information, this form of self-knowledge is evident early in infancy, potentially from birth.

A second form of self, and one also based on perceptual information, is the "interpersonal self," which involves the individual considered from the point of view of engaging in social interaction with others in the world. Again, because the interpersonal self is based on perception, such self-knowledge appears during infancy. Neisser's other forms of the self, the "conceptual," "temporally extended," and "private self," all involve the understanding of different components of the self, covering aspects such as one's beliefs and assumptions about one's self; one's life narratives and memories of the self; and one's thoughts, images, and feelings. These forms of self are based on a variety of types of information and arise in development at varying ages coincident with the child's ability to think, remember, and reason about the self.

Neisser's characterization of the self is coherent and wide ranging, and also provides a framework for examining and understanding the self. Although there exists developmental data pertinent to each of these five selves, this chapter will focus on the first: the ecological self. The most intriguing aspect of the ecological self is its focus on an individual's knowledge of his or her physical body in relation to the external world. As such, a prime example of the ecological self might involve self-knowledge of one's body position in space, along with how one's body subsequently moves through space. Viewed in this way, one pertinent research question is whether young infants show evidence of self-knowledge of body position and movement.

A second point, and one related to the first, is the recognition that such self-knowledge is given through directly available perceptual information. Building on the theoretical ideas of James Gibson (1966, 1979), Neisser assumes that knowledge of the world begins with perception, with our perceptual systems sensitive to information invariantly specifying the objects and events within the world. Moreover, not only are young infants sensitive to such information, but they play an active, exploratory behavior role in uncovering new information (E. J. Gibson, 1987). This focus raises obvious questions about the general nature of the perceptual input specifying our perception of the world, and more specific to the current context, the information underlying one's self-knowledge of one's body position. For Neisser (1991), this information is primarily visual, given that proprioceptive and/or kinesthetic sources (while providing information about movement) vary tremendously with changes in body position and must accordingly be continuously scaled or calibrated to the visual input. It is important to realize, however, that such knowledge is potentially available via all of these sources of information.

If knowledge of body position and movement can arise through multiple input systems, then it becomes critical to explain how these systems not only provide such information, but are also combined and/or integrated by perceivers. Correspondingly, the question now shifts from the ways in which self-knowledge of body position and movement is specified visually to how such self-knowledge is specified through visual and action systems. Understanding the coordination of visual and action systems in providing knowledge about body position is the focus of the work described in this chapter.

The question of whether infants have self-knowledge of their body position, and if so, what the nature of the information is for such knowledge, can be examined across a range of scales or levels. At one level, one can ask about knowledge of limb position: Do infants know where their limbs are in space and how they are moving? This question can be explored within the context of intermodal perception in infancy. At a different level of analysis, one can ask whether infants have knowledge of their general body posture. Essentially, how is one's body oriented with respect to the ground plane? These issues are studied within the context of research on postural control. Another level of analysis involves knowledge of one's dynamic body position: In this case the question is, what do infants know about moving and guiding themselves through the world? These issues can be explored within the context of work on visually guided locomotion. Finally, one can ask about infants' knowledge of their global body position relative to the external environment. Where are we in space, in relation to important objects and/or landmarks? Such issues fall within the province of research on spatial orientation. A common theme of these questions is whether infants exhibit these various forms of self-knowledge of body position and movement, and how such knowledge might be due to integrating visual information with proprioceptive and kinesthetic system information.

Self-knowledge of Limb Position and Movement

The first context in which to examine self-knowledge of body position involves recognition of limb position and movement: This question can be interestingly explored within the realm of intermodal perception in infancy. Generally, there exists strong evidence that young infants coordinate information arising from different perceptual systems. Numerous studies suggest that by the age of 5 months, infants recognize object properties such as shape, substance, and texture on the basis of visual and haptic system information (see Bushnell & Boudreau, 1991, 1993; Rose & Ruff, 1987; Spelke, 1987, for reviews). Is there any corresponding evidence that infants use intermodal information for recognizing their own limb position and movements? This form of intermodal perception requires integrating visual information with kinesthetic and proprioceptive inputs, which results in knowledge of limb movement and position.

Two experimental results have demonstrated that infants, in fact, do evidence such intermodal perception (Bahrick & Watson, 1985; Rochat & Morgan, 1995). In a series of studies, Bahrick and Watson (1985) examined visual-proprioceptive intermodal perception of the leg movements of 3- and 5-month-old infants. In this work, infants kicked their legs while sitting in an infant seat — such kicking provided proprioceptive information for leg movement. While kicking their legs, infants participated in a preferential looking task with two video monitors containing different visual images. On the first monitor, infants saw a live, on-line version of their own leg movements. Because the visual movement on this display was correlated with their own movement, it was referred to as the "contingent" display. On the second monitor, infants saw a videotape of a different child in the same situation (or, in one of the experiments, a previously recorded videotape of their own legs). Because the movement in this display was unrelated to their own movement, it was called the "noncontingent" display.

If infants discriminate between these displays, they should show preferential fixation to one of the monitors. According to Bahrick and Watson (1985), the most likely basis for this discrimination would be the detection of the contingency between the proprioceptive information for movement and the visual movement occurring on one of the monitors. The results of a series of studies convincingly demonstrated intermodal perception, with the 5-month-old (but not 3-month-old) infants preferentially fixating one of the displays. Somewhat counterintuitively, infants in these studies did not prefer an intermodal match, but instead preferred to fixate the noncontingent display. Although various explanations for such preferential fixation can be offered, this work does demonstrate that 5-month-old infants detect their own leg movements on the basis of visual and proprioceptive information.

Rochat and Morgan (1995) have extended these findings by examining the nature of the visual information necessary for performing such visual-proprioceptive intermodal recognition. Similar to Bahrick and Watson (1985), the preferential fixation of 3- and 5-month-old infants to two on-line video images of their moving legs was observed. In one study, left-right spatial directionality was reversed on one of the video monitors, thereby producing a mismatch between the perceived proprioceptive direction of movement and the seen visual direction of movement; on the other, left-right spatial directionality was retained. Infants in this situation looked longer and kicked more while attending to the left-right reversed monitor, which suggests that this display was perceived as spatially noncongruent.

A recent series of experiments conducted in my laboratory (Schmuckler, 1994) provides strong convergent evidence for the findings of Bahrick and Watson (1985) and Rochat and Morgan (1995). In this work, visual-proprioceptive perception of arm and hand movements (rather than leg movements) was examined, with the focus again on exploring the visual information necessary for intermodal perception. In this work, 5-month-old infants performed hidden arm and hand movements (as opposed to the leg movements of Rochat & Morgan, 1995) while simultaneously viewing a contingent display (an on-line image of their own hand) and a noncontingent display (a previously recorded videotape of a different child in the same situation). The logic of these experiments was identical to that of Bahrick and Watson (1985) and Rochat and Morgan (1995): If infants perceive their own limb movements, they should preferentially fixate one of the two displays.

Three experiments tested this hypothesis. An initial study was designed as a simple replication of the previous experiments, to ensure that infants have visual-proprioceptive intermodal detection of arm and hand movements. The second experiment extended these results by again exploring the importance of spatial directionality. Similar to Rochat and Morgan (1995), the left-right dimension of the video image was reversed for the contingent display, thereby producing a situation in which a physical arm and hand movement in one direction resulted in an image in which the hand seemed to move in an opposite direction. A third experiment investigated the importance of the point of observation of the hidden limb by providing a relatively novel view of this limb. In this study, the camera focused on the child's hand was positioned on the floor, facing upwards, producing an image displaying the palm of the hand with the fingers pointed downwards and the wrist and arm of the hand at the top of the screen. Such an image is novel in that it does not correspond to the image of the hand naturally seen from one's own view (an "egocentric" view) or from that of another individual looking at someone (an "observer" view).

Figure 1 presents the results of these three experiments, shown in terms of infants' percent looking times toward the contingent and noncontingent displays. Replicating and extending Bahrick and Watson (1985) and Rochat and Morgan (1995), Experiment 1 demonstrated 5-month-olds' significant preferential fixation toward the noncontingent display, thereby suggesting visual-proprioceptive intermodal discrimination. In contrast, infants in Experiment 2 did not preferentially fixate either the contingent or noncontingent display, which again demonstrates that left-right spatial reversal disrupts intermodal perception. Experiment 3 once again produced significant preferential fixation of the noncontingent display, implying that the point of observation for the hidden limb is relatively unimportant, with infants able to detect their own limb movements despite seeing this limb from a novel orientation. Interestingly, the interpretation of these results converges with those of Rochat and Morgan (1995), despite differences in the experimental setup of these studies, as well as the specific pattern of results of this work. As such, these studies provide a nice example of the principle of converging operations using discrimination measures (Garner, Hake, & Erikson, 1956; Proffitt & Bertenthal, 1990).

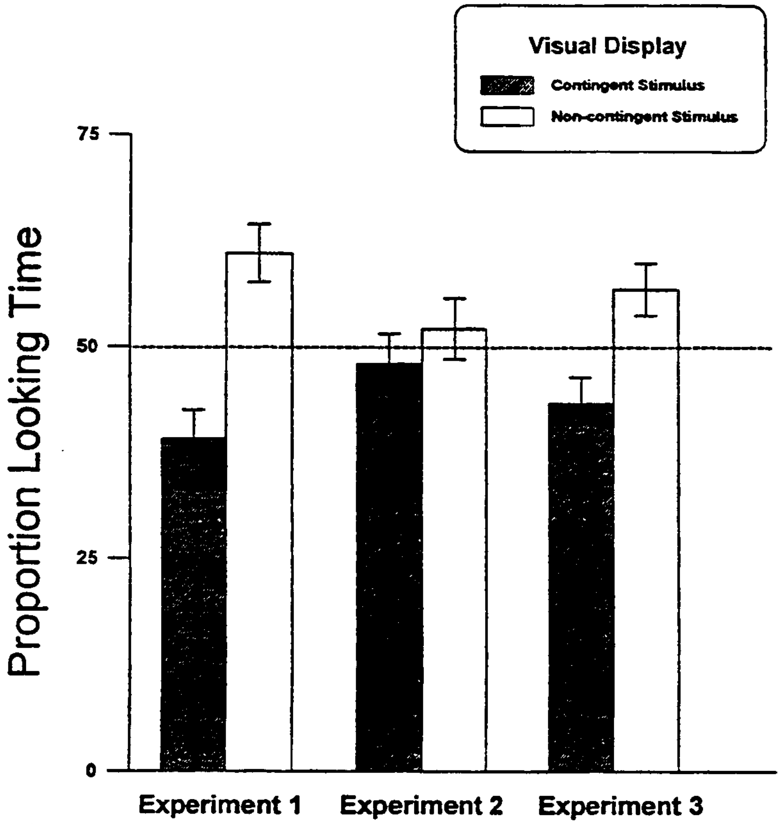

FIGURE 1. The mean proportion of looking time, and standard error, toward the contingent and noncontingent visual displays. Equivalent looking (50%) toward the displays is notated with a dotted line.

Together, these results provide compelling evidence that 5-month-old infants coordinate visual and proprioceptive inputs for detecting their own limb movements. Such a finding strongly implies perception of own limb movements, a finding in keeping with Neisser's (1988, 1991, 1993) characterization of the ecological self. The next series of experiments explores evidence for infants' self-knowledge of body posture and orientation.

Self-knowledge of Body Posture and Upright Orientation

A second context for examining self-knowledge of body position involves recognition of body posture and/or upright orientation on the basis of visual and action system information. What is the information used for maintaining body posture? Obviously, one knows about body posture through vestibular, kinesthetic, and proprioceptive inputs (e.g., Nashner & McCollum, 1985). Less obvious, however, is that visual information is critical for the control of stance and posture. One of the most compelling demonstrations of this effect was provided by David Lee and colleagues (Lee & Aronson, 1974; Lee & Lishman, 1975; Lishman & Lee, 1973), in their experiments using the "moving room." A moving room, which is an enclosure consisting of three walls and a ceiling that moves back and forth atop a stationary floor, simulates the optical information arising from a loss of posture. For an observer standing within a moving room, movement of the walls produces a perceived loss of stability in the opposite direction, resulting in compensatory postural sway in the same direction as room movement. Intriguingly, these compensatory responses occur despite the fact that both vestibular and kinesthetic inputs indicate postural stability.

The moving room has also been used to examine visual control of posture in developmental contexts. Lee and Aronson (1974), for example, found that newly standing infants were dramatically influenced by such visual information, with wall movements producing postural instabilities such as sways, staggers, and falls; similar results have been found in other studies examining both static (Bertenthal & Bai, 1989; Stoffregen, Schmuckler, & Gibson, 1987) and dynamic (Schmuckler & Gibson, 1989; Stoffregen, Schmuckler, & Gibson, 1987) postures. Other researchers have provided evidence that these postural reactions are present early in infancy (Bertenthal & Bai, 1989; Butterworth & Hicks, 1977; Gapenne & Jouen, 1994; Jouen, 1984), appearing coincident with the onset of crawling (Bertenthal & Bai, 1989; Higgins, 1992; Higgins, Campos, & Kermoian, 1993; but see Jouen, 1984, for conflicting results).

These moving room results support the idea that infants and toddlers have knowledge of body posture and upright orientation on the basis of perceptual and action system information. Interestingly, although it is clear that even young infants use visual information for postural control, there are also dramatic developmental changes in this visual control of posture. One area that has been examined involves postural responses to moving visual information as a function of the frequency and/or amplitude of that movement (Brandt, Dichgans, & Koenig, 1973; Lestienne, Soechting, & Berthoz, 1977; Stoffregen, 1986; van Asten, Gielen, & van der Gon, 1988). For example, van Asten et al. (1988) observed that adults' postural compensation to visual rotations around the line of sight fell off for rotations above the frequency of about 0.3 Hz; accordingly, it appears that adults do not use relatively high-frequency visual information for balance control.

In contrast, there exists compelling evidence that young infants and toddlers do use high-frequency visual information for maintaining equilibrium (Bai, 1991; Delorme, Frigon, & Lagace, 1989). Bai (1991), for example, examined the postural responses of seated 5-, 9-, and 13-month-old infants to visual oscillations occurring at 0.3 and 0.6 Hz. In this work, the 9- and 13-month-old infants responded to both speeds of movement, although there was no systematic postural response for the 5-month-old, prelocomotor infants. In the same vein, Delorme et al. (1989) found appropriate postural compensations to visual oscillations of 0.52 Hz for standing children. Similar developmental differences between infants/young children and adults have been found for the amplitude (i.e., gain) and timing (e.g., latency to respond) components of postural sway.

I am currently exploring (Schmuckler, 1995a) such developmental differences in the visual control of posture by focusing on children between the ages of 3 and 6 years. This age range is of interest because it conceivably represents a transitional period in the adoption of adultlike postural control (Ashmead & McCarty, 1991; Shumway-Cooke & Woollacott, 1984). Although the details of this work are outside of the purview of this chapter (because of the somewhat older subjects involved), its findings are intriguing. A series of studies have replicated the results of Bai (1991) and Delorme et al. (1989) in finding that children use high-frequency visual information for postural control; accordingly, children react in a nonadultlike fashion in terms of the frequency of their postural response. In contrast to these findings, children responded in an adultlike manner in the timing of their postural reactions, relative to the visual movement. Finally, the amplitude of children's postural responses demonstrated a mixture of adult- and nonadultlike responding. Together, these findings suggest that the postural sway of 3- to 6-year-old children is characterized by both adultlike and nonadultlike responding; speculatively, this mixed developmental profile might represent a transitional state in postural control. More generally, these findings are revealing in light of the question of infant's and children's self-knowledge of body posture, supporting the idea that children know about their body's upright orientation on the basis of perceptual and action system information.

Self-knowledge of Body Movement and Action Capabilities

The previous section suggested that infants and children have self-knowledge of their body's upright orientation in static postures. It is also possible to examine self-knowledge of body movements in dynamic situations by looking at toddlers' knowledge of their own large-scale body movements through the environment. One domain in which such questions can be explored is that of visually guided locomotion. Visually guided locomotion, which refers to the ability to guide ones' self through the world while avoiding obstacles and moving through openings, has been suggested as a fundamental skill involved in the growth of independent mobility, and requires sophisticated integration of visual information with motor behavior (Gibson & Schmuckler, 1989).

Visually guided locomotion has been examined both developmentally and with adult subjects. Work with adults has focused on delineating the optical information important for the control of locomotion (J. J. Gibson, 1958; Lee, 1974; Lee & Lishman, 1977) or with examining the effects of visual guidance on kinematic parameters of gait (Patla, 1989; Patla, Prentice, Robinson, & Neufield, 1991; Patla, Robinson, Samways, & Armstrong, 1989; Warren, Young, & Lee, 1986). In contrast, developmental work has explored the growth of skills necessary for visually guided locomotion, such as spatial orientation (e.g., Cornell, Heth, & Broda, 1989; Herman, 1980; Rieser, Doxsey, McCarrell, & Brooks, 1982), the development of detour behavior (Heth & Cornell, 1980; Lockman, 1984; Mckenzie & Bigelow, 1986), the perception of surface properties relevant for independent locomotion (Gibson et al., 1987), and so on.

Some research with young toddlers has focused specifically on the impact of visually guided locomotion on kinematic parameters of gait (Palmer, 1987, 1989; Schmuckler, 1990, 1993a; Schmuckler & Gibson, 1987). Schmuckler and Gibson (1989), for example, examined the impact of guidance around obstacles on responses to optical flow information imposed by a moving room. Examining children between 1 and 3 years of age, divided into three groups based on their locomotor experience (novice, intermediate, expert), they found increased postural perturbation in response to movement of the room when children performed a route-finding situation (walking around obstacles), relative to when no obstacles were present in the child's path. In contrast, there were no differences in postural perturbations as a function of the presence versus absence of obstacles when children stood still within the room, which indicates that the increased response in the presence of obstacles was specific to route finding.

Subsequent analyses of the videotapes explored gait perturbations (noticeable accelerations and decelerations in walking speed) as a function of visual guidance conditions. Interestingly, and in contrast to analyses of postural instabilities, gait perturbations produced in response to room movements decreased in the presence of obstacles, relative to when no obstacles were present, with this difference disappearing for the oldest, most experienced group of walkers. Thus, visual guidance produced a more rigidly controlled locomotor style at younger ages. This finding is in keeping with the idea that novice performers of a motor act try to reduce the degrees of freedom relating to that behavior (Bernstein, 1967; Newell & Corcos, 1993; Woollacott & Sveistrup, 1994). With increasing skill and experience, however, these actors release this stiffness, which results in less constrained movements.

In a similar vein, Schmuckler (1990, 1993a) explored the impact on kinematics of gait of locomoting through environments requiring varying degrees of visual guidance. In this work, 14-month-old toddlers locomoted along a path free of obstacles (the "free locomotion" condition), a narrow path requiring regulation of gait but no route-finding (the "controlled locomotion" condition), and a path requiring guidance around obstacles (the "guided locomotion" condition). Analyses of gait kinematics revealed that visual guidance conditions significantly impacted on the child's step size (but not on walking speed), with step size systematically decreasing as the environment required higher degrees of visual guidance. Again, this finding is in keeping with the idea that visually guided locomotion produces a more rigid gait, with this rigidity expressed as a more conservative step size.

A final series of experiments (Schmuckler, 1993b, 1995b) examined visually guided locomotion using a somewhat different route-finding situation — children's navigation over barriers. Although the details of this work are, again, beyond the scope of this chapter, it will be briefly described. The primary goal of this research was to examine whether visually guided locomotion was related in some way to children's intrinsic knowledge of their own locomotor abilities, or to action capabilities, or was scaled to the child's body size. For example, recent research with older children and adults suggests that action in the world is often "body-scaled," that is, related to physical body dimensions (Burton, 1992; Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Konczak, Meeuwsen, & Cross, 1992; Mark, 1987; Mark, Baillet, Craver, Douglas, & Fox, 1990; Mark & Vogele, 1987; Pufall & Dunbar, 1992; Warren, 1984; Warren & Whang, 1987).

One project examining such questions (Schmuckler, 1993b) explored 12-, 18-, and 24-month-old toddler's abilities to successfully cross over a barrier to reach their parent, seated on the other side. Crossing behavior to barriers of various heights was coded using a scheme by Adolph (in press), in which crossing was categorized as a "success" (crossing the barrier without disturbing it), a "failure" (attempting to cross the barrier but ultimately knocking it over), or a "refusal" (not attempting to cross the barrier). The results of this study revealed that at all ages, children successfully crossed the barriers at low heights, with the mean number of failures increasing as the barrier height increased. Interestingly, as the barrier continued to rise in height, the number of failures in barrier crossing actually decreased, accompanied by a corresponding increase in the number of refusals shown by children. This finding that children will refuse to even attempt to cross barriers at certain heights is very much in keeping with the idea that toddlers have knowledge of their body capabilities, with their subsequent action reflecting this self-knowledge.

Subsequent analyses examined whether the ability to successfully cross over barriers was related in some fashion to the child's actual capabilities for action in the world. Toward this end, thresholds for barrier crossing were calculated as the barrier height at which successfully crossing occurred 50% of the time. Not surprisingly, mean crossing thresholds increased with age. These thresholds were then investigated with reference to the factor(s) that might account for variation in these thresholds between the different age groups. Toward this end, crossing thresholds were normalized by dividing each child's threshold by either body dimensions or locomotor skill measures. If thresholds are related to these dimensions, then this normalization should remove the differences between the ages. The different normalizing factors investigated included the child's standing height, sitting height, leg length, body weight, walking experience (as given by parental report), and age. Intriguingly, the only factor that eliminated the differences in crossing thresholds between the age groups was each child's walking experience.

Generally, the studies on visually guided locomotion support the idea that toddlers have self-knowledge of both their body movement and their action capabilities. The pattern of success, failure, and refusal rates suggest that children had knowledge of their locomotor capabilities, in that they did not attempt to cross barriers at heights that could not yet be successfully negotiated. In addition, crossing thresholds were related to children's overall locomotor skill, as indexed by walking experience. This result is especially interesting in light of the current evidence suggesting that for adults and older children, the successful accomplishment of a number of motor activities (e.g., stair climbing, sitting, reaching, and gap crossing) are related to body dimensions (Burton, 1992; Carello et al., 1989; Konczak et al., 1992; Mark, 1987; Mark et al., 1990; Mark & Vogele, 1987; Pufall & Dunbar, 1992; Warren, 1984; Warren & Whang, 1987). In contrast, research with infants and toddlers has found such relationships with skill measures, not body dimensions. Adolph (in press), for example, found that toddler's abilities to successfully climb up and down slopes was related primarily to walking skill.

Self-knowledge of Body Orientation in Space

The final area to be described concerns knowledge of body position on a more global, environmental scale. In this case, the primary issue involves examining infants' and toddlers' spatial orientation abilities, or self-knowledge of body position in space, relative to environmental landmarks. As in the previous sections, one of the focal concerns here involves understanding how perceptual and action systems contribute to knowledge of where one is in the world, as well as how such knowledge is modified or updated subsequent to some form of movement through the environment. For example, when an observer moves through the world, there exist multiple sources of information for how the world changes that accompany this movement. Assuming the environment is lit, visual input provides information for the changing spatial relationships in the world. Along with this visual information is information arising from the movement of one's body — kinesthetic, proprioceptive, and vestibular inputs — that specifies movement through space. Rieser and colleagues (Rider & Rieser, 1988; Rieser, 1979, 1983; Rieser, Guth, & Hill, 1986; Rieser & Heiman, 1982; Rieser & Rider, 1991) have elegantly demonstrated that both older children and adults use such "body movement" information for spatial orientation. In contrast to the information accompanying self-movement, when an object moves relative to one's self, the only information specifying such movement is visual. Accordingly, movement of objects in the world produces only a single source of information for a change in spatial relationships.

How do these differences in the available information for spatial orientation affect infants' and toddlers' knowledge of the spatial layout? Bremner (Bremner, 1978a, 1978b; Bremner & Bryant, 1977) explored this question by examining 9-month-old infants' abilities to find a hidden object (a modified stage IV search task), following either infant self-movement through the world or following object movement through the world. In keeping with the above analysis on the informational sources available for spatial updating, infants successfully retrieved the toy more often subsequent to self-movement, relative to object movement, through the world. This result has been replicated by other researchers examining 6- to 7-month-old infants (Bai & Bertenthal, 1992) and suggests that the availability of multiple cues for spatial change leads to better spatial updating than the presence of only a single source of information for such change.

One way in which these findings are limited is that they do not provide a thorough exploration of the relative importance of visual and body movement information for spatial orientation. A pair of experiments recently completed in my laboratory attempted to evaluate the impact of these two input sources on spatial updating. In these studies, infants between the ages of 9.5 and 18 months were seated in front of a table and saw a toy hidden in one of two locations (different colored cups) on the table. Prior to being allowed to search and retrieve this toy, infants experienced one of two displacements: Either they were moved 180° around the table (the "infant displacement" condition), or the table was moved 180° around them (the "table displacement" condition). Accordingly, infant versus table displacements manipulated the presence versus absence of body movement information. Visual information was manipulated by performing infant and table displacements with the lights on or off. Using these manipulations enabled us to systematically examine the impact of visual and body movement information on infant spatial orientation and to assess infants' abilities to integrate these inputs during spatial updating.

These two experiments were distinctive in that they provided different cues for successful performance. In the first experiment, the hidden toy always ended up on the same side of the table (relative to the infant) throughout the experiment, with the visual characteristics of this hiding position (i.e., the color of the cup) varying randomly from trial to trial. In the second experiment, the location of the hidden toy was signaled visually, with the color of the correct location constant throughout the experiment. However, the actual side on which the hidden toy was located varied throughout the study. Thus, in the first study, infants needed only learn a particular motor sequence to retrieve the hidden toy (e.g., search in the cup to their right), whereas in the second study, infants needed only learn a color association (e.g., search in the red cup). Both experiments also explored search performance developmentally, with the first study testing 9.5-, 14-, and 18-month-old infants, and the second study employing 9.5- and 16-month-old infants. Examining search performance with these different age groups was of interest, given previous results (e.g., Acredolo, 1978, 1979; Acredolo & Evans, 1980) that suggested significant developmental change in spatial orientation abilities across this age range.

The results of these experiments are presented in Figure 2, which graphs the mean number of times infants successfully retrieved the toy (out of four possible trials) as a function of body movement information (infant versus table displacement) and visual information (lit versus dark environment) conditions. Because there were no significant age effects in either study, these data are shown averaged across age. The most interesting result was the significant interaction between visual and body movement information conditions. In both studies, search performance was best when both visual and body movement sources provided information for spatial updating. In contrast, search in the remaining three conditions led to equivalent, or worse, performance. Intriguingly, cuing the correct location visually (Experiment 2) led to somewhat better search performance than cuing the location with a motor response (Experiment 1), although both studies produced the same pattern of results. Together, these findings suggest that visual and body movement information interact in spatial updating, with visual information possibly playing a more important role than body movement information.

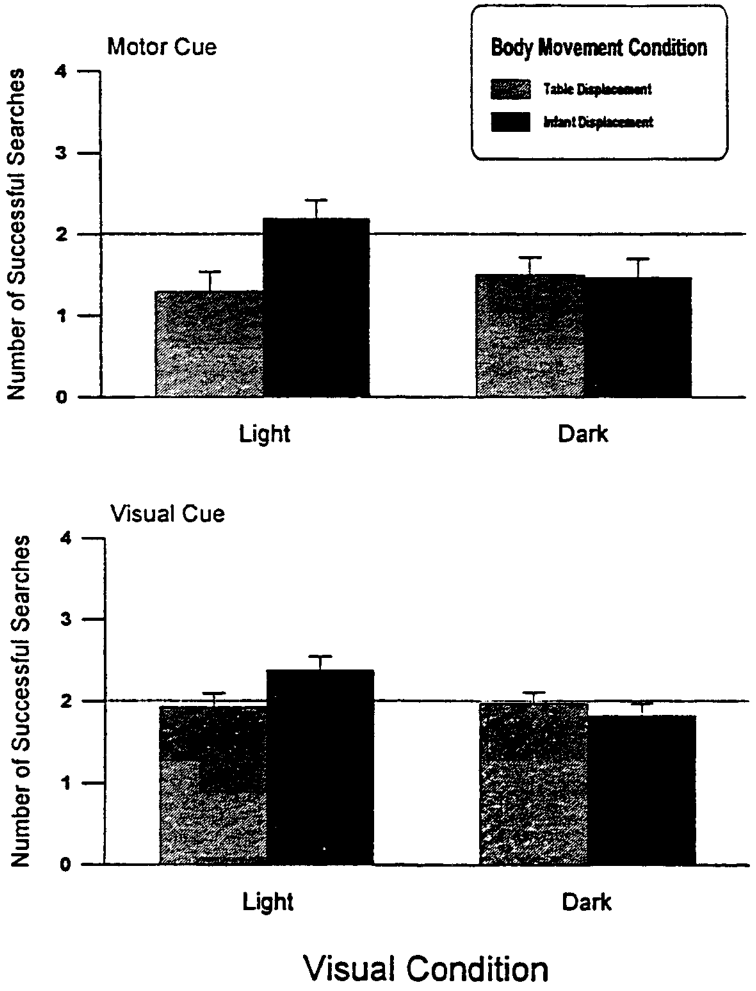

FIGURE 2. The mean number of successful searches (out of 4), as a function of body movement and visual conditions. The top panel shows search performance when the location of the hidden toy was signaled using a motor cue, and the bottom panel shows search performance when the location of the hidden toy was signaled using a visual cue. Chance performance is notated with a horizontal line.

More generally, the results of these studies are in keeping with the idea that infants have self-knowledge of their global body position in space. This ability to update their spatial orientation, while limited, is present at a fairly young age (9.5 months), although it appears to undergo little developmental change (at least as measured by the current paradigm) across the age range examined.

Summary and Conclusions

A variety of different experimental paradigms and results have supported the idea that infants perceive their own body position in space. This knowledge has been seen to exist at a variety of "levels," from knowledge of individual limb movements to knowledge of one's spatial orientation within the larger environment. Accordingly, this work provides evidence in support of Neisser's (1988, 1991, 1993) notion of the ecological self, or knowledge of the physical self in relation to the physical environment. Because this information for self arises through directly available perceptual information, the ecological self is presumably present early in life. The studies described in this chapter support this hypothesis, suggesting that the ecological self might be a very early component or form of the growing child's self-concept.

In keeping with Neisser's emphasis on the importance of perceptual information, the work described here explored the information giving rise to this self-knowledge. One inescapable conclusion drawn from this work is that there are multiple sources of information that can be used for knowing about one's body position and movement in space. This chapter has concentrated on the use and integration of visual and action system information, and has found that even young infants integrate such information to inform themselves about their body's orientation. Thus, although Neisser has focused on the importance of visual information for the ecological self, it seems clear that the ecological self is a joint product of a multitude of information sources.

A number of issues and questions have been studiously avoided in this chapter. One conspicuously absent concern is the issue of whether the types of self-knowledge exhibited by infants in these studies represent implicit or explicit awareness. Unfortunately, given the obvious limitations of dealing with infant subjects, it is difficult to imagine how one would gain direct experimental insight into this question. Hence, the question of whether this self-knowledge is implicitly or explicitly represented remains unresolved. Speculatively, one possibility is that the explicitness of the different types of self-knowledge discussed in this chapter change as this knowledge becomes more global. For example, visual-proprioceptive intermodal perception of limb movements seems, intuitively, to be an unlikely candidate for explicit self-knowledge, particularly with 5-month-old subjects. In contrast, the research on visually guided locomotion and spatial orientation intuitively seems to convey more explicit aspects of self-knowledge of body position and capabilities. Although one obvious confounding factor is the general age difference of the participants in these situations, the idea that explicit self-knowledge might increase with increasing scales of body movement and position is an intriguing possibility.

Finally, although it seems clear that infants make use of different forms of information for self-knowledge of body position, the use and integration of such information must undergo developmental change. For example, the research briefly described on the visual control of posture outlined a fascinating developmental progression in the use of certain types of visual information for balance control, and highlighted the fact that infants and young children make use of visual information to which adults appear insensitive. Similarly, the work on spatial orientation implies a significant developmental change in spatial updating, although this suggestion arises through the notable failure to find developmental differences across a wide age range. One of the more general goals of future research is to identify the ways in which the use and integration of information sources change as a function of age, as well as identifying the factors underlying such changes.

In sum, the work described in this chapter has provided evidence that infants, at a very young age, express some self-knowledge pertaining to their body position and movement, and their capabilities for action. More globally, this work has attempted to understand how children perceive and act, and how perceiving and acting within the environment fits into the larger framework of the emergence of the child as an active, independent agent in the world.

NOTES

The research described in this report and the writing of this manuscript were supported by a grant from the Natural Sciences and Engineering Research Council of Canada. Correspondence concerning this article can be addressed to: Mark A. Schmuckler, Division of Life Sciences, University of Toronto, Scarborough College, Scarborough, Ontario, Canada, M1C 1A4, or by electronic mail at: marksch@lake.scar.utoronto.ca.

REFERENCES

Acredolo, L. P. (1978). Development of spatial orientation in infancy. *Developmental Psychology, 14*, 224–234.

Acredolo, L. P. (1979). Laboratory versus home: The effect of environment on the 9-month-old infant's choice of spatial reference system. *Developmental Psychology, 15*, 666–667.

Acredolo, L. P., & Evans, D. (1980). Developmental changes in the effects of landmarks on infant spatial behavior. *Developmental Psychology, 16*, 312–318.

Adolph, K. E. (in press). A psychophysical assessment of toddlers' ability to cope with slopes. *Journal of Experimental Psychology: Human Perception and Performance.*

Ashmead, D. H., & McCarty, M. E. (1991). Postural sway of human infants while standing in light and dark. *Child Development, 62*, 1276–1287.

Asten, W. N. J. C. van, Gielen, C. C. A. M, and van der Gon, J J. D. (1988). Postural movements induced by rotations of visual scenes. *Journal of the Optical Society of America, 5*, 1781–1789.

Bahrick, L. E., & Watson, J. S. (1985). Detection of intermodal proprioceptive-visual contingency as a potential basis of self-perception in infancy. *Developmental Psychology, 21*, 963–973.

Bai, D. L. (1991). *Visual control of posture during infancy.* Unpublished doctoral dissertation., University of Virginia.

Bai, D. L., & Bertenthal, B. I. (1992). Locomotor status and the development of spatial search skills. *Child Development, 63*, 215–226.

Bernstein, N. (1967). *Coordination and regulation of movement.* New York: Pergamon Press.

Bertenthal, B. I., & Bai, D. L. (1989). Infants' sensitivity to optical flow for controlling posture. *Developmental Psychology, 25*, 936–945.

Brandt, T., Dichgans, J., & Koenig, E. (1973). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research, 23*, 471–489.

Bremner, J. G. (1978a). Spatial errors made by infants: Inadequate spatial cues or evidence of egocentrism? *British Journal of Psychology, 69*, 77–84.

Bremner, J. G. (1978b). Egocentric versus allocentric spatial coding in 9-month-old infants: Factors influencing the choice of code. *Developmental Psychology, 14*. 346–355.

Bremner, J. G., & Bryant, P. E. (1977). Place versus response as the basis of spatial errors made by young infants. *Journal of Experimental Child Psychology, 23*. 162–171.

Burton, G. (1992). Nonvisual judgment of the crossability of path gaps. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 698–713.

Bushnell, E. W., & Boudreau, J. P. (1991). The development of haptic perception during infancy. In M. A. Heller & W. Schiff (Eds.), *The psychology of touch* (pp. 139–161). Hillsdale, NJ: Erlbaum.

Bushnell, E. W., & Boudreau, J. P. (1993). Motor development and the mind: The potential role of motor abilities as a determinant of aspects of perceptual development. *Child Development, 64*, 1005–1021.

Butterworth, G., & Hicks, L. (1977). Visual proprioception and postural stability in infancy: A developmental study. *Perception, 6*, 255–262.

Carello, C., Grosofsky, A., Reichel, F. D., Solomon, Y., & Turvey, M T. (1989). Visually perceiving what is reachable. *Ecological Psychology, 1*, 27–54.

Cornell, E. C., Heth, D., & Broda, L. S. (1989). Children's wayfinding: Responses to instructions to use environmental landmarks. *Developmental Psychology, 25*. 755–764.

Delorme, A., Frigon, J., & Lagace, C. (1989). Infants' reactions to visual movement of the environment. *Perception, 18*, 667–673.

Gapenne, O., & Jouen, F. (1994, June). *Temporal properties of the visuo-postural coupling in newborns.* Poster presented at the 9th International Conference on Infant Studies, Paris, France.

Garner, W. R., Hake, H. W., & Erikson, C. W. (1956). Operationalism and the concept of perception. *Psychological Review, 63*, 149–159.

Gibson, E. J. (1987). Introduction essay: What does infant perception tell us about theories of perception? *Journal of Experimental Psychology: Human Perception and Performance, 13*, 515–523.

Gibson, E. J., Riccio, G., Schmuckler, M. A., Stoffregen, T. A., Rosenberg, D., & Taormina, J. (1987). Detection of the traversability of surfaces by crawling and walking infants. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 533–544.

Gibson, E. J., & Schmuckler, M. A. (1989). Going somewhere: An ecological and experimental approach to development of mobility. *Ecological Psychology, 1*, 3–25.

Gibson, J. J. (1958). Visually controlled locomotion and visual orientation in animals. *British Journal of Psychology, 49*, 182–194.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Harter, S. (1983). Developmental perspectives on the self-system. In P. H. Mussen (Ed.), *Handbook of Child Psychology, Vol. IV: Socialization, personality, and social development* (E. M. Hetherington, Vol. Ed.) (pp. 275–385). New York: John Wiley and Sons.

Herman, J. F. (1980). Children's cognitive maps of large-scale spaces: Effects of *Psychology, 29*, 126–143.

Heth, C. D., & Cornell, E. H. (1980). Three experiences affecting spatial discrimination learning by ambulatory children. *Journal of Experimental Child Psychology, 30*, 246–264.

Higgins, C. (1992, May). *The relation between self-produced locomotion and postural compensation to optic flow.* Paper presented at the International Conference on Infant Studies, Miami Beach, FL.

Higgins, C., Campos, J., & Kermoian, R. (1993, March). *The influence of creeping on infant postural compensation to optic flow.* Paper presented at the 1993 meetings of the Society for Research in Child Development, New Orleans, LA.

Jouen, F. (1984). Visual-vestibular interactions. *Infant Behavior and Development, 7*, 135–145.

Konczak, J., Meeuwsen, J. J., & Cross, M E. (1992). Changing affordances in stair climbing: The perception of maximum climbability. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 691–697.

Lee, D. N. (1974). Visual information during locomotion. In R. B. MacLeod and H. L. Pick (Eds.), *Perception: Essays in honor of James J. Gibson* (pp. 250–267). Ithaca, NY: Cornell University Press.

Lee, D. N., & Aronson, E. (1974). Visual proprioceptive control of standing in human infants. *Perception & Psychophysics, 15*, 529–532.

Lee, D. N., & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies, 1*, 87–95.

Lestienne, F., Soechting, J., & Berthoz, A. (1977). Postural readjustments induced by linear motion of visual scenes. *Experimental Brain Research, 28*, 363–384.

Lishman, J. R., & Lee, D. N. (1973). The autonomy of visual kinaesthesis. *Perception, 2*, 287–294.

Lockman, J. J. (1984). The development of detour ability during infancy. *Child Development, 55*, 482–491.

Mark. L. S. (1987). Eyeheight-scaled information about affordances: A study of sitting and stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 361–370.

Mark, L S., Baillet, J. A., Craver, K. D., Douglas, S. D., & Fox, T. (1990). What an actor must do in order to perceive the affordance for sitting. *Ecological Psychology, 2*, 325–366.

Mark, L. S., & Vogele, D. (1987). A biodynamic basis for perceived categories of action: A study of sitting and stair climbing. *Journal of Motor Behavior, 19*, 367–394.

McKenzie, B. E., & Bigelow, E. (1986). Detour behavior in young human infants. *British Journal of Developmental Psychology, 4,* 139–148.

Nashner, L. M., & McCollum, G. (1985). The organization of human postural movements: A formal basis and experimental synthesis. *The Behavioral and Brain Sciences, 8,* 135–172.

Neisser, U. (1988). Five kinds of self-knowledge. *Philosophical Psychology. 1.* 35–59.

Neisser, U. (1991). Two perceptually given aspects of the self and their development. *Developmental Review, 11,* 197–209.

Neisser, U. (1993). The self perceived. In U. Neisser (Ed.), *The perceived self: Ecological and interpersonal sources of self-knowledge.* (p. 3–24). Cambridge. MA: Cambridge University Press.

Newell, K., & Corcos, D. M. (1993). Issues in variability and motor control. In K. M. Newell and D. M. Corcos (Eds.), *Variability and motor control* (pp. 1–12). Champaign, IL: Human Kinetics.

Palmer, C. F. (1987, April). *Between a rock and a hard place: Babies in tight spaces.* Paper presented at the Biennial Meetings of the Society for Research in Child Development, Baltimore, MD.

Palmer, C. F. (1989, April). *Max headroom: Toddlers locomoting through doorways.* Paper presented at the Biennial Meetings of the Society for Research in Child Development, Kansas City, MO.

Patla, A. E. (1989). In search of laws for the visual control of locomotion: Some observations. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 624–628.

Patla, A. E., Prentice, S. D., Robinson, C., & Neufield, J. (1991). Visual control of locomotion: Strategies for changing direction and for going over obstacles. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 603–634.

Patla, A. E., Robinson, C., Samways, M., & Armstrong, C. J. (1989). Visual control of step length during overground locomotion: Task-specific modulation of the locomotor synergy. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 603–617.

Proffitt, D. R., & Bertenthal, B. I. (1992). Converging operations revisited: Assessing what infants perceive using discrimination measures. *Perception & Psychophysics, 47,* 1–11.

Pufall, P. B., & Dunbar, C. (1992). Perceiving whether or not the world affords stepping onto and over: A developmental study. *Ecological Psychology, 4,* 17–38.

Rider, E. A., & Rieser, J. J. (1988). Pointing at objects in other rooms: Young children's sensitivity to perspective after walking with and without vision. *Child Development, 59,* 480–494.

Rieser, J. J. (1979). Spatial orientation of six-month-old infants. *Child Development, 50,* 1078–1087.

Rieser, J. J. (1983). The generation and early development of spatial inferences. In H. L. Pick & L. C. Acredolo (Eds.), *Spatial orientation in natural and experimental settings* (pp. 39–71). New York: Plenum.

Rieser, J. J., Doxsey, P. A., McCarrell, N. S., & Brooks, P. H. (1982). Wayfinding and toddlers' use of information from an aerial view of a maze. *Developmental Psychology, 18,* 714–720.

Rieser, J. J., Guth, D. A., & Hill, E. (1986). Sensitivity to perspective structure while walking without vision. *Perception, 15,* 173–188.

Rieser, J. J., & Heiman, M. L. (1982). Spatial self-reference systems and shortest-route behavior in toddlers. *Child Development, 53*, 524–533.

Rieser, J. J., & Rider, E. A. (1991). Young children's spatial orientation with respect to multiple targets when walking without vision. *Developmental Psychology. 27*. 97–107.

Rochat, P., & Morgan, R. (1995). Spatial determinants in the perception of self-produced leg movements in 3- to 5-month-old infants. *Developmental Psychology, 31* (4).

Rose, S. A., & Ruff, H. A. (1987). Cross-modal abilities in human infants. In J. D. Osofsky (Ed.), *Handbook of infant development, 2nd Ed.*, (pp. 318–362). New York: Wiley.

Schmuckler, M. A. (1990). Issues in the development of postural control. In H. Bloch and B. I. Bertenthal (Eds.), *Sensory-motor organizations and development in infancy and early childhood* (pp. 231–236). Dordrecht: Kluwer Academic Publishers.

Schmuckler, M. A. (1993a). Perception-action coupling in infancy. In G. J. P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 137–173). Advances in Psychology Series. North-Holland: Elsevier.

Schmuckler, M. A. (1993b, March). *Knee's up Mother Brown: Toddlers' stepping over barriers*. Poster presented at the 60th meetings of the Society for Research in Child Development, New Orleans, LA.

Schmuckler, M. A. (1994, June). *Infant's visual proprioceptive intermodal recognition*. Poster presented at the 9th International Conference on Infant Studies, Paris, France.

Schmuckler, M. A. (1995a, March). *Children's postural sway in response to high and low frequency visual oscillation*. Poster presented at the Biennial Meetings of the Society for Research in Child Development, Indianapolis, Indiana.

Schmuckler, M. A. (1995b, March). *The influence of spatial extent and transparency on toddler's crossing of barriers*. Poster presented at the Biennial Meetings of the Society for Research in Child Development, Indianapolis, Indiana.

Schmuckler, M. A., & Gibson, E. J. (1989). The effect of imposed optical flow on guided locomotion in young walkers. *British Journal of Developmental Psychology, 7*, 193–206.

Shumway-Cooke, A., & Woollacott, M. J. (1985). The growth of stability: Postural control from a developmental perspective. *Journal of Motor Behavior, 17*, 131–147.

Spelke, E. (1987). The development of intermodal perception. In P. Salapatek & L. Cohen (Eds.), *Handbook of Infant Perception, Vol. 2: From perception to cognition* (pp. 233–273), Orlando, FL: Academic Press.

Stoffregen, T. A. (1986). The role of optical velocity in the control of stance. *Perception & Psychophysics, 39*, 355–360.

Stoffregen, T. A., Schmuckler, M. A., & Gibson, E. J. (1987). Use of central and peripheral optical flow in stance and locomotion in young walkers. *Perception, 16*, 113–119.

Warren, W. H. (1984). Perceiving affordances: Visual guidance in stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 683–703.

Warren, W. H., & Whang, S. (1987). Visual guidance of walking through apertures: Body-scaled information for affordances. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 371–383.

Warren, W. H., Young, D. S., & Lee, D. N. (1986). Visual control of step length during running over irregular terrain. *Journal of Experimental Psychology: Human Perception and Performance*, *12*, 259–266.

Woollacott, M. H., & Sveistrup, H. (1994). The development of sensorimotor integration underlying posture control in infants during the transition to independent stance. In S. P. Swinnen, J. Massion, & H. Heuer (Eds.), *Interlimb coordination: Neural, dynamic, and cognitive constraints*. San Diego: Academic Press.